ELECTRO-PHYSIOLOGY

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CHAPTER VI

ELECTROMOTIVE ACTION IN VEGETABLE CELLS

It has long been known that electrical currents can be led off from certain parts of plants, under given conditions. Becquerel, Wartmann, and Buff all made important contributions to this subject. The last author concluded from his experiments (carried out with comparatively imperfect technical accessories) that "the roots and all internal parts of the plant filled with air are in a state of permanent negativity, while the moist or wetted outer surfaces of fresh twigs, leaves, flowers, and fruits are positively electrical" (1). He explained this to mean that the epidermis of the plant forms a dividing line between the external water of moisture and the salts, acids, and other constituents of the sap. Electrical excitation occurs at this boundary, and current flows in the direction observed in the leading-off circuit. Jürgensen (2), again, found the uninjured surface positive to the transverse section, in the divided leaves of *Vallisneria spiralis*, in consequence, as he believed, of chemical differences between the exposed fluid of the cell and the surface of the leaf. The same negativity of injured points (artificial transverse or longitudinal sections) obtains, according to Hermann (3), in living stalks of different species of plants. The cross-section, or artificial long section, is plainly negative to the uninjured surface. The intensity of these currents, "generally speaking, varies in a marked degree with the charge of moisture in the plant, and the resulting conductivity. The deflections range from 20 degrees of the scale to its disappearance from the field of vision. The stalks of fungi yield the strongest currents." The E.M.F. varies between 0·01 and 0·08 Dan., *i.e.* is of approximately the same order as in the muscle current, although the deflections are often

small, owing to the high resistance. In the majority of cases the "longitudinal-transverse" current in divided plant-stalks diminishes rapidly, and may even be reversed. Hermann (who refers these currents, by analogy with the currents of muscle and nerve, to the immediate contact of chemically altered dying and normal plasma in the injured cells) explains this by the individual death of the latter, as Engelmann has said of smooth muscle-cells. "If the opened, or otherwise injured, protoplasmic tubes were continuous throughout the length of the tissue, like the fibres of nerve and muscle, the process of death would creep forward, and the cross-section be permanently negative to the surface of the plant. Most of the cells which contain the protoplasm are, however, short, albeit drawn out longitudinally, and thus the negativity of a cross-section is transitory, although a further section exhibits fresh activity" (*l.c.*).

Much greater interest attaches to the electrical reactions which may appear in certain organs of plants that are perfectly uninjured. The name of Burdon-Sanderson is foremost in these researches. His admirable observations on the excitable leaf of *Dionæa muscipula* are by far the best contribution to the subject. Later on we shall have to study these in detail; here it need only be said that differences of potential are also found in the totally uninjured leaf, particularly between upper and under surface, and exhibit perfectly regular variations during the excitatory movements of the plant.

A. J. Kunkel (4), working under Sachs' direction, concluded, from the green foliage-leaves of different kinds of plants, that (on leading off with unpolarisable electrodes, under uniform conditions) the veins of the leaf were positive to its green surface. "The stout mid-rib is weakly positive to the finer lateral veins; in the latter the junction of two veins is a highly positive point." According to Kunkel, the sign of this P.D. depends essentially upon the state of imbibition at the leading-off contacts at the moment, since every point that has been moistened for some time is at first positive to points that have been more recently wetted.

And if these experiments indicate the great significance of the distribution, or movement, of water in vegetable organs, with reference to their electromotive activity, the same appears still more plainly from Kunkel's experiments as to the effects of injury

and flexion on the development of differences of potential. On leading off from two points of a green stem which is in itself isoelectric, a P.D. always appears when the vicinity of one electrode is injured (by cutting or squeezing), that electrode being invariably negative to the other. The same occurs on bending the stalk, if this is effected by a sudden jerk. Slow, regular flexion, on the contrary, produces no effect on the galvanometer. The electrodes were prevented, by threads, from shifting along the stalk.

The theoretical conclusion from these experiments (which were subsequently confirmed by O. Haake, 5) was, like Grünhagen's theory of the manifestations of animal electricity, referred to the so-called diaphragmatic currents, nor did it obtain longer than the former—once more proving that it is not sufficient, in explanation of a physiological phenomenon, to bring forward a single, purely physical, symptom, but that we are in presence of a vital manifestation, the intrinsic character of which is determined by a complex interaction of physical and chemical forces.

In the "migration of water" Kunkel believed that he had discovered an infallible, and universally applicable, key to the electrical phenomena which may at times be observed in vegetable organs. In the case of his fundamental experiment with green leaves, he ascribes the observed differences in potential to the differing resistance presented by the tissues, at the leading-off contacts, to the water, which diffuses inwards from the moist electrodes, thus bringing about the requisite movement of water. And indeed the unequal moisture of the ribs and mesophyll is an easily-verified fact in many leaves. But, as Haake points out, the leaf may be sponged over, or covered permanently with water, *without alteration of the electromotive reaction.* Even more convincing is the reaction of permanently submerged leaves (*Vallisneria, Nitella*), "from which regular currents can be led off even when they lie under water (to the depth of $\frac{1}{2}$–1 mm.)." Haake further remarks "that a normal electrical reaction is exhibited only in the living leaf. A leaf killed by momentary immersion in boiling water gives no more reaction if left one to two days in the moist chamber, than a leaf that has died naturally, and yet the conditions for quantitative differences in the migration of water are still present."

And against the validity of the "drop experiment" Haake

urges that it succeeds even when applied to a leaf of which the tissues are fully saturated by long immersion in water, "so that there can be no further absorption of water from the electrodes."

The chief point insisted on by Kunkel is the fact that electromotive action appears only with rapid, and not with slow, flexion of a green stalk. But without denying that electrical effects *might* be caused in dead or living parts of plants by rapid and adequate movements of water (due to purely mechanical causes), it is equally certain that they are not under all conditions *solely* due to the migration of water. This is sufficiently plain from the experiments on excitable leaves, to which we shall return later. Above all, an explanation is needed of the differences in potential (often permanent and very considerable) which frequently make their appearance in certain vegetable organs, and which, from the point of view we have been discussing, would present insuperable difficulties to Kunkel; for it is hardly a satisfactory or probable explanation that derives the strong "current of rest," amounting to 0·1 Dan. (which Kunkel found in the leaf of *Mimosa*, on leading off from the upper border of the excitable pulvinus at the base of the common [primary] leaf-stalk, and from one of the two strong thorns near the insertion of the leaf), from "the diffusion currents obtained, even in the resting state, on moistening certain portions of tissues that are peculiarly adapted to rapid alteration in their charge of water, taking it up and giving it out quickly in large quantity." Kunkel, however, concerned himself little with the electromotive reactions of *excitable* parts of plants (which are theoretically of fundamental importance), and his researches in this direction are superseded by the later investigations of Burdon-Sanderson.

The intrinsically smaller differences of potential which Kunkel observed in different species of green leaves must equally, according to Haake, be referred to vital physiological processes. In the first place, there is an obvious relation between the electromotive manifestations and respiration. When suitable leaves or stalks were enclosed in a glass tube, with the electrodes inserted into one end, while gases were led through the other (Fig. 137), there was invariably a rapid diminution of the original P.D. between mid-rib (close to its entrance into the stalk) and mesophyll (near the centre of the leaf), if the oxygen was completely driven off by moist hydrogen. With the readmission of air the current

approximately recovered its former strength. The same reaction occurred in seedlings of *Pisum sativum* on leading off from the collar of the root and the stem, where Hermann (3) had previously found a normal strong current, the root being negative to the body (*i.e.* the cotyledons). The E.M.F. often exceeded $\frac{1}{10}$ Dan. Johannes Müller-Hettlingen (3), who studied this effect more closely at Hermann's request, formulated the law as follows: When one of the leading-off electrodes is persistently applied to the cotyledons, while the other leads off successively from points of the seedling above or below the cotyledon, there is always a current directed from the electro-positive seed husk, or cotyledon,

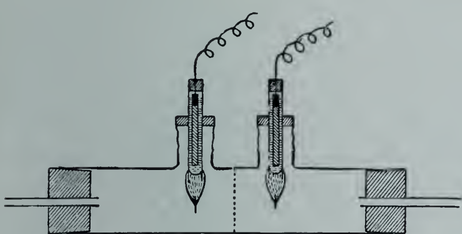

FIG. 137.

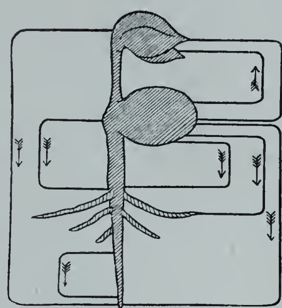

FIG. 138.

to all other electro-negative parts of the seedling, its E.M.F. being less in proportion as the exploring electrode is nearer the cotyledon, above or below it. Fig. 138 gives a schema of this reaction.

Haake occasionally found reversal, or augmentation, instead of diminution, of the original current when respiration was interrupted. "Such parts of plants as naturally exhibit marked differences in respiration yield excessively strong currents, *e.g.* the reproductive organs of flowers, on leading off from pistil or anther, and flower-stalk." In such cases Haake obtained deflections of 50–80 degrees on the capillary electrometer, while in green leaves the total effect is only 15–20 degrees.

The P.D. is also, comparatively speaking, very marked when the respiration of a plant is checked at one electrode only, by cutting off the supply of oxygen, which Haake effected by enclosing seedlings of *Pisum* or *Faba* in a double tube, and replacing the air by hydrogen on one side only (Fig. 137). In one speci-

men (a seedling of *Pisum* 14 days old), the initial deflection of + 5 degrees rose on leading off from collar of root and tip of stalk to + 57 degrees, after driving off the oxygen from the root and lower part of the stem, falling again with a fresh supply of air to + 14 degrees. With uninterrupted supply of air, the same effect results from local changes in respiratory activity due to rise or fall of temperature in the plant, near one or the other electrode.

The assimilatory process seems, from Haake's experiments, also to contribute to the differences of potential exhibited by green leaves. The arrest by darkness of the decomposition of CO_2 regularly produces a diminution of the initial current. "If the normal conditions are restored (by illumination), the former potential reasserts itself; but its magnitude is permanently affected, and becomes either less or greater." Leaves that contain no chlorophyll (petals of flowers) show no change of electrical response when they are deprived of light. The most important fact in these observations is the existence of an electrical P.D. between the cells, or, strictly speaking, tracts of cells, in a vegetable organ or entire plant, which differ in their chemical constitution.

The electromotive reactions of vegetable organs (for the most part very inconspicuous as compared with the corresponding manifestations in animal tissues) have attracted much more attention since the discovery of the striking manifestation in *excitable plants*, as first pointed out by Burdon-Sanderson, when he showed that the excitatory movements of the leaf of *Dionæa muscipula* are accompanied by highly characteristic alterations of the original P.D. between upper and under surface (6).

The subject is best introduced by describing the organisation and structure of the parts of plants involved, as well as the nature and causes of their excitatory movements.

The general habit of growth in *Dionæa muscipula* is shown in Fig. 139, which at the same time gives the method employed by Munk (to whom we owe an admirable work on the electromotive action and excitatory movements of this plant, 7) for setting up the specimens he investigated, so as to lead off from the leaves as conveniently as possible.

The leaf, which is from 2 to 12 cm. long in the full-grown plant, is divided externally into three sections—the winged leaf-stalk, its unwinged part, and the lamina of the leaf. This last

consists of two distinct lobes, which, like the wings of the petiole, are attached to the highly convex mid-rib. At its margin the leaf is prolonged at tolerably regular intervals into bristle-like processes, which hook together alternately when the lobes are folded up. On the surface of each lobe are three small hairs, one

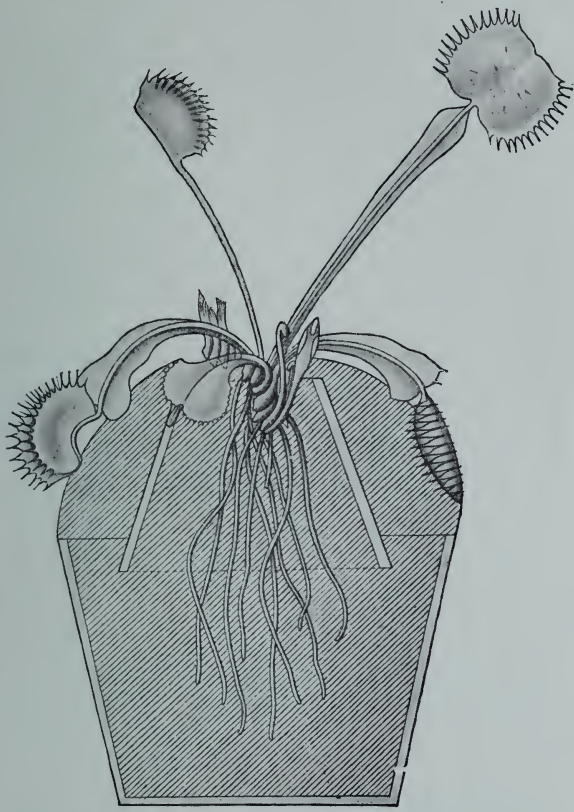

Fig. 139.

near the mid-rib, the other two somewhat external to it, and these are essentially the seat of excitability. The inner surface of the leaf is further provided with a number of small discoid glands. The wings of the petiole consist of a soft unstable tissue, while the lobes are lumpy, sappy, and highly resistant. Lateral veins run out at approximately equal distances from the fibro-vascular bundle which passes up the centre of the mid-rib, and form an elegant system of arches at the margin of the

leaf (Fig. 140). The parenchyma of the lobe is entirely composed of elongated or oblong cells, their long axis being parallel with the main bundles of the lateral veins, and vertical to the mid-rib (Fig. 141), while they are circular (in the long section of the leaf) in cross-section. Large intercellular lacunæ appear between the single cells.

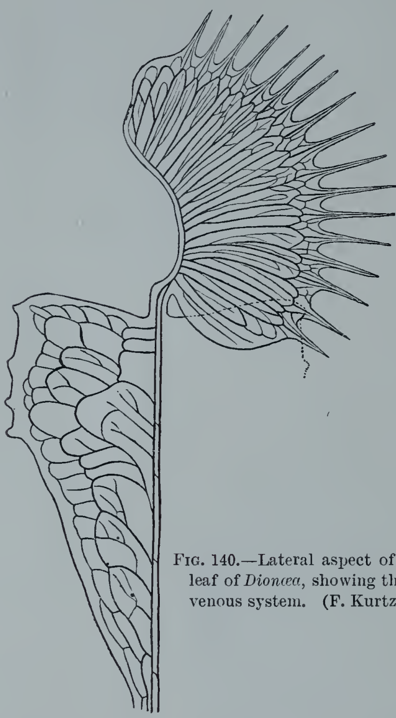

Fig. 140.—Lateral aspect of a leaf of *Dionæa*, showing the venous system. (F. Kurtz.)

Below the epidermis of the upper surface of the leaf, the oblong hexagonal cells of which are rich in starch, lies a layer of somewhat shorter thin-walled cells, succeeded by 2–3 layers of larger, longer, cylindrical cells, with hardly any organised contents (Fig. 141). "The innermost layer of these cells impinges on the long slender cells which accompany the fibro-vascular bundles in the petiole. Below the vascular bundle there are

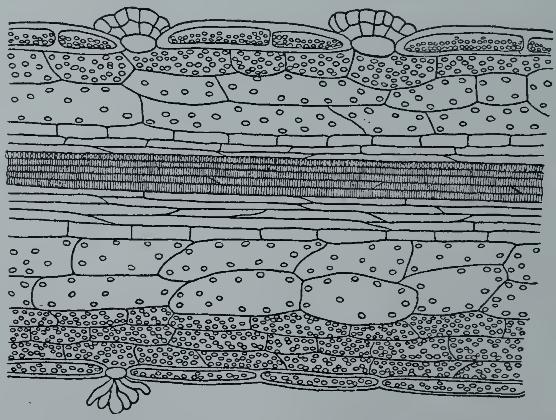

Fig. 141.—T.S. of lamina of *Dionæa* leaf, parallel with the lateral nerves. (F. Kurtz.)

2–3 rows of cells resembling those described above, then 3–4 layers

of much smaller, less conspicuous cells, rich in chlorophyll, and finally, the epidermis of the under surface of the leaf" (F. Kurtz).

The parenchyma of the leaf breaks through the epidermis of the inner surface at the point where a sensory hair takes origin. The parenchymatous cells lying immediately below the epidermis are smaller at this point, and form a cylinder (circular in cross-section) consisting of 4–5 layers of polygonal cells, which rise above the surface of the leaf, and constitute about $\frac{1}{10}$th of the total length of the hair. From this cylinder the true hair rises as a slender cone; it contains no vascular bundle, and consists of long small cells (F. Kurtz, 8).

If unpolarisable electrodes are applied to opposite ends of a fresh uninjured leaf of *Dionœa*, a regular current (as first pointed out by Burdon-Sanderson) is indicated on a galvanometer included in the circuit, flowing in the leaf from the end proximal to the stalk (according to Munk, the *anterior* end) to the distal (*posterior*) end—Sanderson's "normal leaf current." On leading off from symmetrical points of the external (under) surface of the lamina, Munk either found no current, or a weak, irregular effect. If lines are conceived on the surface of a lobe, at right angles to the mid-rib (Munk's "transverse-lines"), each point of the same will be negative to the corresponding point of the mid-rib, the more so within a certain range in proportion as the point upon the transverse line is nearer the margin of the leaf. The line connecting the most negative points of all the cross-lines running approximately parallel with the mid-rib is called by Munk the "principal longitudinal line" of the lamina; as the most positive point of the leaf he opposes the anterior end of the posterior third of the mid-rib. The distribution and magnitude of potential at the upper (inner) surface of the leaf corresponds, according to Munk, with that of the lower (outer) surface; so that on leading off from two corresponding points of both surfaces there should be no current; this, as Burdon-Sanderson found later, is not the case. The electromotive reactions of the leaf of *Dionœa* are associated with its vitality, and at death decline to zero. The absolute magnitude of E.M.F. is of considerable proportions. "The P.D. between a point in the proximity of the principal longitudinal line, and one in the posterior half (distal to the stalk) of the mid-rib, is not infrequently 0·04–0·05 Dan."

In order to explain these electromotive effects in the "resting" leaf, Munk formulated a "molecular theory," in which the parenchyma cells function as cylindrical molecules, giving such an electrical reaction that "the positive electricity is directed from the middle of the cell towards either pole, the latter being therefore positive towards the centre." *Dionæa* (in common with a few other plants) has the power of making visible movements under special conditions, consisting in this case of a rapid closing of the two lobes, which enables it to capture the insects that have alighted on it. This kind of excitatory movement is distinguished by its rapid energetic character from the slow "movements of absorption" which commonly succeed the first, and only appear alone when absorbable substances (meat, albumen, etc.) are applied cautiously, and without touching the sensitive hairs, to the inner surface of the leaf. The excited leaf of *Dionæa* closes with extreme rapidity (in a minute at the longest), while the reopening may extend over many hours (24–36). If the leaf has closed on an absorbable substance it may not reopen for several days.

The whole inner (upper) surface of the leaf is sensitive, yet, as was said above, it is chiefly the six hairs (three sessile on each lobe) which are so strikingly excitable that they were long held to be the only sensitive part. Amputation of the petiole, or division of the joint between leaf and stalk, does not act as a stimulus unless the incision reaches the lower border of the mid-rib of the leaf, where the vertical rows of excitable parenchyma cells are situated beneath the epidermis of the upper surface. Amputation of the marginal bristles is equally ineffective. On the other hand, incision of the lobe at any point induces closure.

Slight pressure has no effect upon the upper surface of the lamina, while stronger pressure, as well as stroking with a pointed needle, discharges an excitatory movement. The lower surface is totally insensible to all these stimuli. Only the upper layer of the parenchyma of the lobe and mid-rib is therefore excitable and conductive, agreeing with the fact that the hairs (which are not intrinsically excitable) are sessile upon the cones of excitable parenchyma cells that break through the epidermis, and act upon these something after the manner of a lever (cf. taste-hairs of certain animals). Each hair can be shorn away from apex to base with sharp scissors without evoking any excitatory movement,

till the cone-like protuberance of the parenchyma of the lobe is reached, when the contact at once causes the leaf to fold together.

Along with these mechanical irritants we must include the abstraction of water, as a stimulus to the excitable parenchyma at the base of the hair. Darwin (9) found, on placing the leaves of *Dionæa* in concentrated solution of sugar, or even on applying a single drop to an excitable hair, that the laminæ closed up immediately. Munk observed the same effect with alcohol and concentrated salt solution, and again when the plants were exposed to rapid evaporation in dry air.

The movements of the leaf of *Dionæa*, like all movements of plants, are due to processes that cannot be compared with the contraction phenomena of muscle, or with any true contractile tissue. They are much rather special instances of cell co-ordination, depending on quite different mechanical principles. The most characteristic type of plant-movement is the well-known *Mimosa pudica*. Each leaf-stalk of the "sensitive plant" bears four secondary petioles, provided in their turn with two rows of leaflets. During the day the principal stalk is erect, the secondary petioles being spread out like the fingers of a hand. The single leaflets are expanded into a smooth surface. At night the leaves sink down, the secondary petioles are folded together, and the leaflets stand up, so that the inverted surfaces are in contact. This change of position in all the leaves can be induced in the day-time also by violently shaking the plant, or bringing it into an atmosphere of chloroform or ether vapour. Locally, however, or within a limited tract, the same effects occur on mechanically exciting the single leaflets (by touching, pricking, cutting), particularly at the point where the principal leaf-stalk is attached to the stem. Here there is a cushion (*pulvinus*), which is similarly developed at the base of the second and third petioles. In every case an excitatory movement is discharged only on touching the under side of the swelling at the joint, while the upper surface is almost entirely non-excitable.

Anatomical investigation of one of these swellings shows it to be traversed by a vascular bundle with a layer of very succulent cells between the bundle and the green cortex; these cells are tolerably thick-walled upon the upper (insensitive) side of the joint, while on the lower side the walls are comparatively slender. On bisecting the swelling transversely, a funnel appears on

either side (as was pointed out by Brücke, 10); this is due to an initial tension in the living plant between the succulent cells of the pulvinus and the vascular bundle, "so that on cutting through it the cellular portion tries to expand in the direction of the long axis, while the central vascular bundle cannot lengthen beyond its original proportions. It may be compared with an inextensible wire drawn through a piece of gutta-percha, and screwed against the end of it with a nut" (Brücke). This may occur when a leaf-stalk changes its position, tension being raised in the upper half of the swelling, or diminished in the lower.

It is easy to prove that the second alternative invariably occurs in excitation. On comparing the colour of the excitable under surface of a pulvinus before and after stimulation, a striking difference is apparent. Before excitation it is light green, afterwards it is a darker colour. There can be no doubt that this change is due solely to the discharge of fluid from the cells into the large intercellular spaces previously filled with air, and obviously there must be extension and relaxation of the layers of tissue involved in the process. The fact that any excitation of the under side of the motor organ (cushion) of *Mimosa*, however scrupulously localised, discharges water from *all* cells of the parenchyma, testifies to the propagation in all other cells of the under surface, of certain alterations of protoplasm in the cells directly excited, which result in the discharge of water. Pfeffer, indeed, saw the darker colour spreading "like lightning" from the point excited. Thus within the pulvinus itself there is conductivity of excitation from cell to cell.

Still more striking, however, is the fact that the stimulus can be transmitted over large tracts, and even to the most remote parts of the plant. The external features of this phenomenon are so well known that it is superfluous to dilate on them, but the correlative internal processes must be briefly referred to. The account given by Haberlandt (11) in his treatise on the "sensitive plant" will be followed substantially.

Dutrochet (12) endeavoured to determine which parts of the plant served to transmit the excitation. He showed that the cortex was not involved, by paring away a ring of it, when the conductivity of the twig remained unaffected. So, too, on removing the pith. The wood alone was involved, without exception, or more correctly the fibro-vascular system (bast and vessels).

Dutrochet also pointed out that the transmission of excitation depended on the movement of fluid contained in the conducting elements. This view was subsequently confirmed by the experiments of Meyen (13), Sachs (14), and Pfeffer (15). Meyen observed that a drop of fluid was exuded on cutting the stalk of *Mimosa,* immediately before the excitatory movement of the leaf. This drop of fluid, which starts out instantaneously if the leaf or stalk of *Mimosa* is wounded, has been an important factor in nearly all the proposed explanations of conductivity, and formed the basis of the "physical" theory. Sachs (*l.c.* p. 482) concludes, from the rapid exudation of a drop of water from the incised wood, that the fluid in the fibro-vascular bundles stands at very high pressure in a sensitive mimosa, the excitable parenchyma cells of the lower half of the pulvinus being also in the highest degree turgescent. "The water thus tends on the one hand to exude from the endosmotically over-filled cells of the pulvinus, and on the other, to penetrate them, on account of its high pressure in the woody bundle." In the unexcited plant these pressures are at equilibrium. Incising the stalk disturbs the balance, the water in the wood migrates towards the wound, pressure diminishes, and the water filters out of the highly turgescent excitable parenchyma of the pulvinus into the walls of the cells. Here it follows the direction of diminishing tension, and flows towards the woody bundle of the axial cord. The excitatory movement appears along with the diminished turgor of the lower portion of the pulvinus.

From this point of view the true excitable cells are found in the parenchyma of the lower side of the pulvinus only, where any stimulus renders the plasma permeable to water, which then filters through the cell-membrane into the intercellular spaces. *The relation between distant pulvini would thus be purely physical,* caused by the tension of a constant mass of water in the woody parts of the plant. There is, however, another alternative, which may seem *a priori* the more probable. *Excitable cells may be present in the vascular bundles also, and propagate the stimulus from joint to joint.* This theory finds substantial confirmation in the discoveries of Tangl, Russow, and Gardiner (*Art. d. bot. Inst. zu Würzburg,* iii. 1884) in reference to the connection of adjacent cell-bodies by fine protoplasmic threads. Such a connection was actually found to exist between the cells of the

excitable parenchyma of the pulvinus, and it was natural to assume similar bridges between the latter and the cells of the conducting vascular bundles. The effect of local narcosis (ether or chloroform) offered a simple means of deciding the question. Claude Bernard pointed out that the excitability of *Mimosa* can be temporarily abolished by etherisation. If this is true of the excitable parenchyma of the cushion, it may be conjectured that the excitable cells of the vascular bundles will exhibit the same reaction. The transmission of excitation should be abolished by local narcosis. But the experiments undertaken by Pfeffer (15) pointed to the contrary result. When the central portion of a secondary petiole was treated with chloroform or ether, an injury-stimulus was always—a mechanical stimulus sometimes—transmitted over the narcotised area. Pfeffer therefore concluded "that migration of water is the sole cause of the propagation of a stimulus. This movement of water takes place in the vascular bundles. If excitation is produced by incision of a vascular bundle, so that fluid exudes from the wound, the disturbance of equilibrium in the water distributed in the bundle depends upon *abstraction* of water. If, on the other hand, excitation is by a mechanical stimulus, a certain, albeit inconsiderable, quantity of fluid passes out of the excited parenchyma of the joint into the vascular bundle; migration is due to the *addition* of water" (Pfeffer, *l.c.* p. 315). In either case Pfeffer refers the propagation of the stimulus from vascular bundle to excitable parenchyma of pulvinus, and *vice versa*, to the migration of water. The disturbance of equilibrium is transmitted to the innermost layers of the parenchyma, immediately adjacent to the bundle, where it acts "as a mechanical stimulus," and discharges the movement.

Further confirmation of this theory appears in the observations of Haberlandt. He finds that excitation in *Mimosa* is propagated even over *dead* tracts of the petiole, destroyed by scalding. If this were entirely the case, it would be conclusive evidence that the conductivity of *Mimosa* depends not upon a connected system of excitable, or conductive, cells in the vascular bundle, but upon a disturbance of hydrostatic equilibrium due to the injury, and transmitted indifferently over the dead zone of the petiole. Migration of sap would in the same sense lead to conductivity of excitation.

Haberlandt localises this process in certain funnel-shaped cells, situated in the leptoma of the vascular bundle (soft bast); the structure of these cells is so far remarkable that each transverse wall bears a single large pit, closed by a porous membrane, and traversed by plasma threads from the adjacent cells. Although these "conducting" cells are in juxtaposition with the ring of collenchyma which surrounds the central bundle of the pulvinus (the cells of which are again connected by plasma bridges with those of the conducting parenchyma), Haberlandt refuses to admit any direct connection between the conducting cells and the collenchyma. There must thus be two systems of cells, functionally co-ordinated, but not in direct conducting, *i.e.* plasmatic, connection.

Haberlandt's theory assumes a very high hydrostatic pressure of sap in the intact conducting cells of the leptoma, which gives elastic tension to the longitudinal walls of the conducting cells; the resulting wall tension represents the immediate source of pressure which, on injury to the conducting system, causes a movement of the sap towards the seat of the sudden diminution of pressure. Clearly this can only be possible on the supposition of a filtration of sap from within the cell, through the intact cross-walls of the adjacent cells. And this entails the further and somewhat improbable assumption that the plasmatic layer covering the pit must invariably be permeable, in a high degree; for thus only is it possible that the conducting cells should act as a system of fused and communicating hollow spaces.

The next point is the mode in which, under the above presumptions, the flow of water within these funnel-cells can act as a stimulus upon the excitable parenchyma of the pulvinus.

Haberlandt refers the propagation of the stimulus entirely to alterations of form and volume in the conducting tissue or excitable parenchyma, correlative with variations of pressure. "When, in consequence of injury to stem or petiole, there is a sudden fall of turgor from the adjustment of differences of pressure in the conducting cells bordering on the collenchyma ring of a joint, the contracting walls of these cells (which are diminishing in diameter) exert a powerful traction on the adjacent collenchyma. Owing to the pliability of the latter this tug is easily transmitted through the ring (which is 2–3 layers deep) to the most internal layer of the excitable parenchyma. If the mechanical force of

the traction corresponding with a single impact is sufficient, an excitatory movement will be discharged, and the cells contracting from loss of water stimulate all the other excitable cells of the joint by means of the pull they exert" (Haberlandt, *l.c.* p. 53). It is still harder to explain the mechanism by which a stimulus is propagated from the relaxed parenchyma of the curving pulvinus to the excitable parenchyma of an adjacent joint, after a single mechanical stimulus, or with chemical or thermic excitation. In this case the pressure associated with the relaxation of the excitable half of the joint, and resulting curvature, could alone effect a possible disturbance of hydrostatic equilibrium in the conducting system, adequate for the transmission of a stimulus. And when Haberlandt compares the resulting movement of the sap "to that within an india-rubber tube containing water at a given hydrostatic pressure, in which increase of pressure at any point is propagated in the form of an undulatory wave from one end of the tube to the other," the anatomical relations of the conducting cells hardly seem to justify such a presumption. The experiments on the conductivity of *Mimosa* would have to be scrupulously repeated before forming any final judgment, and the galvanic effects of excitation might prove a convenient instrument for further investigation.

However this may be, it is in other cases certain that conductivity depends upon excitation of the plasma of the connected cells: and this must be true of *Dionæa.*

As in *Mimosa,* the visible excitatory movements are effected by migration of water, and the normal position of the non-excited leaf is the result of equilibrium between two forces, one of which tends to close the leaf, the other to open it. The cells of the upper surface of the resting (open) leaf are highly turgescent, like those of the under side of the pulvinus in *Mimosa.* If, as was observed by Munk, we picture the cushion of the primary leaf-stalk of *Mimosa* as flattened out superficially, with the characteristic veins in place of the wood-mass, we have physiologically a lobe of *Dionæa,* save that the excitable side is turned downwards; while if two such altered pulvini are imagined, so connected at a right angle that the excitable parenchyma of the swellings is uninterrupted at the point of junction, the entire leaf is practically before us.

The upper layer of cells exerts pressure upon the lower, so

that the equilibrium is balanced as follows: on the lower side the compressed tissue endeavours to extend itself and to increase its length; on the upper there is a marked turgescence, counteracted by the elasticity of the cell-membranes which tend to contract upon themselves. When, in consequence of excitation, water is discharged from the cells of the upper surface, the equilibrium is disturbed (Batalin, 16), and a new state induced, characterised by an actual relaxation and shortening of the upper layers. This cannot, even in the closed leaf, amount to perfect equilibrium, since it is hindered by the contact of the lobes in juxtaposition.

This is plainly seen from the fact that, after cutting off one lobe near the mid-rib, the other, in its excitatory movements, is jerked far beyond the position it occupied in the closed and uninjured leaf. Hand in hand with the shortening of the upper layers at closure, there is a corresponding lengthening of the lower, so that each lobe passes from downward to upward concavity. On opening the leaf, the reverse processes occur. The previously relaxed and diminished cells of the upper parenchyma swell out as turgor increases, and recover their former tension. According to Darwin's measurements, the shortening of the upper layers in a lobe 10 mm. broad reduces it to 0·6 mm. only. This is most obvious when, after taking away one half of a leaf, two points are marked on both upper and lower surface of the other half, and a movement excited; the distance of the marks alters in an opposite direction.

Along with these excitatory movements of the leaf of *Dionæa* (as also of *Mimosa*) there are very striking electromotive effects, which, as was said above, were first recognised by Burdon-Sanderson to be a "negative variation." As the result of his first observations he communicated the following propositions:

(*a*) If the leaf is laid on the electrodes, so that the normal current is manifested on leading off from both ends of the leaf by a deflection of the magnet to the left, and a fly is then made to creep on to it, the needle will swing to the right at the moment when the fly reaches the interior of the leaf, and touches the sensitive hairs of the upper surface, the leaf closing over the fly at the same moment.

(*b*) After the fly has been captured, the needle swings to the right each time that it makes a movement.

(*c*) The same series of manifestations occurs if the sensitive

hairs are touched with a fine brush, or if two platinum electrodes are plunged downwards into the leaf, and lead in the current from an induction coil. The phenomena vary according as the leaf is stimulated at different parts of its upper surface. Excitation of the centre appears to be the most effective, being followed by a negative variation after an interval of $\frac{1}{4}$–$\frac{1}{2}$ sec.

Munk, on leading off from the two ends of the mid-rib on the lower surface of the leaf, without, or even with, compensation of the current flowing from base to apex, invariably observed a diphasic variation, *i.e.* a positive preceded by an initial negative variation, and this is equally the case when all visible excitatory movement of the leaf is wanting. Sometimes Munk even saw a positive effect before the initial negative phase, resulting in a complicated triphasic variation; this only appeared when the excited leaf exhibited an actual movement. When there was at first no difference of potential between the two leading-off points, the diphasic variation still appeared with excitation, the mirror moving rapidly in the direction of an ascending current, and then giving a much weaker deflection in the opposite direction. On leading off from two points of the under surface of the leaf, taken on the same "transverse line," median to the "principal longitudinal line," the excitation either produced a pure positive variation, or at most gave a trace of initial negativity. All these electrical processes fall mainly within the mechanical, and easily detected, latent period, *i.e.* the interval between the moment of excitation and beginning of the final movement of the leaf. From the standpoint of Munk's theoretical construction of the leaf of *Dionœa* out of electromotive elements ("peripolar" cells), there are three alternative explanations of the two successive and opposite phases of which each variation consists; and these are so closely interwoven with the facts actually observed by Munk, that, as Burdon-Sanderson has pointed out, it is exceedingly difficult to separate observation from theory.

(1) In the diphasic variation, as in the diphasic action current of nerve and muscle, the electromotive elements at the two contacts may not be simultaneously affected by the excitatory change (negative variation of E.M.F.); (2) the elements may all be affected simultaneously, and in the same direction—which would be opposite in the two phases; or (3), as Munk

proposes to the exclusion of the first two alternatives, there may be two different kinds of electromotive elements, which are affected in opposite directions by excitation, the variation reaching its maximum in one set later than in the other. "In consequence of excitation," says Munk, "the cells of the upper parenchymatous layer of the leaf and upper mid-rib undergo a negative, those of the under layer and under mid-rib a positive, variation; *i.e.* the negativity of the middle of the cells to their poles diminishes, in consequence of excitation, in the first-named cells, and increases in the second. These changes must be propagated from the seat of excitation through the entire cell-mass with great rapidity, in a period that is small in comparison with the duration of the process in the single cells, since otherwise differences in electrical manifestations could not fail to appear according to the seat of the stimulus." Munk therefore believes the electrical process to be for practical purposes *simultaneous* in all the cells affected, which—in so far as the transmission is plasmatic—is, in view of the very low rate at which excitation is propagated in vegetable protoplasm, in itself highly improbable. But as a matter of fact, Munk's fundamental theory of the peripolar activity of the cells of the leaf-parenchyma hardly calls for contradiction, since it is modelled upon Du Bois's molecular theory, applying it to visible elements, of which the structure and function are *a priori* exclusive of any such conception. It is a purely arbitrary presumption to regard the centre of the cells involved as permanently negative to the two ends, and is indeed impossible where the plasma exhibits any streaming movements.

The later investigations of Burdon-Sanderson (17) have rendered these phenomena more intelligible.

In order, from the outset, to exclude the excitatory movements of the leaf, the two lobes were fixed in plaster of Paris attached to the ends of the mid-rib, while a strip of dry wood was further fastened with gypsum between the two edges of the lamina to the marginal bristles (Fig. 142). A favourable temperature (32°–35° C.) was maintained, and the plant kept in a moist chamber.

As regards electromotive action during rest, the important fact appears in contradiction to the earlier conclusions of Munk, that in an overwhelming majority of cases the two opposite

surfaces of each lobe of the leaf, external and internal (or upper and lower), give a different electrical reaction, so that on leading off from opposite points of the upper and lower surface, there is found to be current, either so that the latter is positive to the former (which Burdon-Sanderson at first held to be normal) or *vice versa*. The degree of positivity, and corresponding magnitude of P.D. and of the leaf-current, in the first case, depend, as soon appears, essentially upon the physiological state of the leaf, and above all upon the previous excitation.

If, after compensating the current of rest, mechanical or other stimuli are sent in moderately rapid succession into a leaf of which the under surface is already positive, there is without

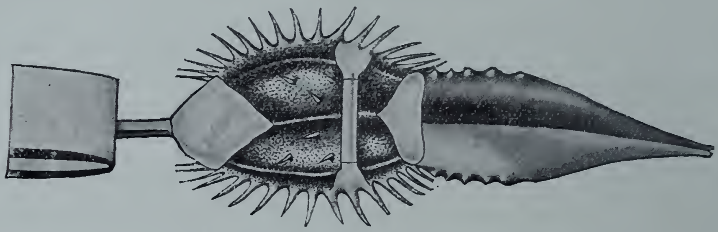

FIG. 142.

exception a marked rise of positivity in the excited surface. It is only by degrees, during the subsequent period of rest, that the current diminishes, until with the same lead-off there is complete isoelectricity, and finally, as has been said, a current in the opposite direction, corresponding with negativity of the under (external), and positivity of the upper (internal), surface of the leaf—a state which, according to Burdon-Sanderson's later observations, must be regarded as normal in the leaf which has remained a long time unexcited. In this instance the leaf-current must, in regard to the internal surface, be regarded as outgoing.

Excitation in such a case is naturally followed by the opposite alterations, as in an initially ingoing leaf-current: the positive upper surface becomes suddenly negative to the lower surface, so that the leaf-current is once more ingoing. It should also be remarked that the lower surface of the leaf is the less positive and more negative, in proportion with the time that has elapsed since the last excitation. The current of rest, on the contrary, is at all times dependent on the previous excitation of

the leaf, and must with an ingoing direction be regarded in a certain sense as its after-effect.

Under these conditions it is clear that the manifestations of excitation must be studied before the state of rest. In leading off from the upper and lower surface of a lobe, one unpolarisable electrode being situated between the three sensitive hairs, the other directly opposite on the lower (external) surface, and then exciting the other lobe of the leaf mechanically or electrically (as in Fig. 143), a diphasic variation appears each time, as can easily be photographed with the capillary electrometer (Fig. 144).

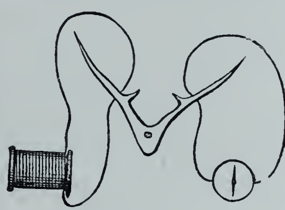

FIG. 143.

In the case of a leaf "modified" by previous excitation, where the lower surface is already positive to the upper, the current is in the first place reversed shortly after stimulating, the lower surface becoming rapidly negative. After about half

FIG. 144.—Photographic record of the variations of an ingoing leaf-current, when one lobe is electrically excited. The interruptions of the black line correspond with breaks in the primary circuit of the induction-apparatus. Interval between the excitations about 5 secs. Rapidity of plate about 1 cm. in 2 secs. (Burdon-Sanderson.)

a second this phase will have reached its maximum, and a second (somewhat slower) and opposite phase sets in, which is, however, less marked, and reaches its maximum in about $1\frac{1}{2}$ sec. after excitation. This, as shown by the photogram, decreases very gradually, and loses itself in the after-effect described above, which is characterised by increased positivity of the lower surface of the leaf; it follows that the second phase is distinct in the *first* excitation only, those immediately subsequent producing merely a simple, monophasic variation. A long interval

is required, in which the positivity of the lower surface diminishes slowly, before the second phase again appears distinctly. The stronger the positivity of the lower surface *ab initio*, the less can it be increased by excitation of the leaf, and conversely, the plainer will be the primary opposite variation.

In an unmodified leaf with outgoing leaf-current (Burdon-Sanderson's "descending" current), the variation consequent on excitation is again found, on leading off from opposite points of the respective surfaces, to be diphasic. The first "entering" phase (ascending in the leading-off circuit), which lasts about a second, and in which the upper and previously positive leaf-surface

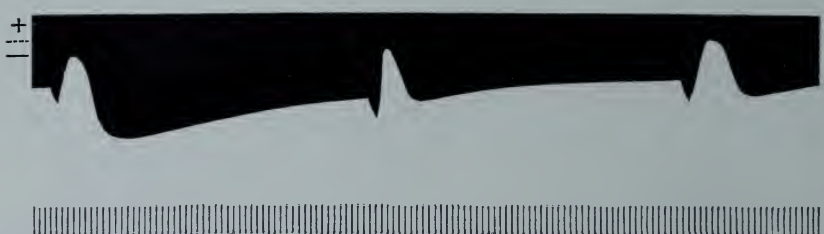

FIG. 145.—Photogram of the variations of an outgoing leaf-current, on exciting one lobe and leading off from the other (cf. Fig. 143). 10 divisions of the time-marking correspond to 1 sec. (Burdon-Sanderson.)

suddenly becomes negative, is often preceded by a momentary alteration in the opposite direction, as shown in Fig. 145. Here again the opposite (outgoing or descending) "after-effect" (second phase) only appears plainly in the first excitation, and owing to its very slow decline is wanting in those that immediately succeed it.

The most important conclusion from these observations is that the leaf of *Dionæa* is excitable in both the unmodified and the modified condition, independent of the direction of the rest current, save that the galvanic effects of excitation are reversed *pari passu* with the reversal of the current of rest.

It is evident that the "modifications" of the leaf-current consequent on repeated excitation are only the after-effect of the slowly declining second phase of the excitatory variation. For exact measurements of time, as well as of the E.M.F. of the variation, Burdon-Sanderson employed a pendulum myograph arranged as a rheotome, which in swinging past opened three keys in succession (Fig. 146). Opening K1 caused a "break" induction

shock (0·1 sec. after liberating the pendulum); opening K2 unbridged the galvanometer circuit, which was broken, finally, by opening K3. The distance between K1 and K2, as also between K2 and K3, is variable. We shall return later to the results of these experiments; here it is sufficient to note that Burdon-Sanderson, with the help of the compensating method, determined the E.M.F. of the first phase at about 0·08 Dan., while that of the second did not exceed 0·82 Dan.

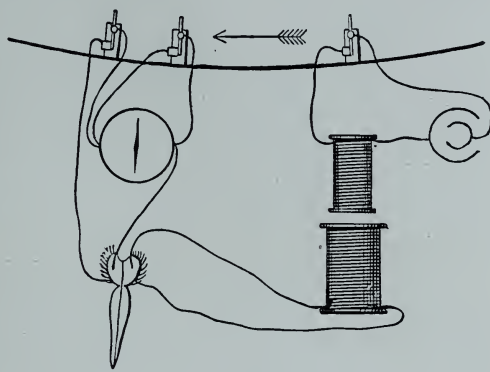

FIG. 146.

If one or other half of the leaf is excited by break induction shocks (the electrodes being usually applied, as in Fig. 143, to opposite and approximately central points of the two leaf-surfaces), the coils of the induction apparatus must be pushed tolerably close (about 10 cm.) before an effect is produced. The direction of the induced current is by no means immaterial, since the effect appears much sooner when the current flows from upper to under surface than in the opposite case. The same applies to battery currents also. If a current, of moderate strength, adequate for excitation, is sent transversely through one half of the leaf in the direction of upper to lower (ingoing), it will be found on leading off from the other half that an excitatory variation of the leaf-current occurs, as a rule, at closure only. Stronger currents (1 Dan. to 2 Groves), on the contrary, excite on opening also, and with a long closure (30 sec.) produce as the visible sign of *persistent excitation* a whole series of oscillations of the leaf-current, which occur at irregular intervals during the passage of the current.

Summation of stimuli may also be demonstrated in the *Dionœa* leaf, if stimuli (break induction shocks) are used of such low intensity that a single shock is inadequate to produce an effect, the interval between the stimuli being less than 0·4 sec. At 0·5 sec. the result becomes uncertain. This applies both to mechanical and to galvanic effects of excitation.

The "modified" state of the leaf in which, as we have stated,

the under surface is positive to the upper, appears not only in consequence of quickly repeated mechanical or electrical excitations, but also as the after-effect of the prolonged passage of a constant current. If such a current is led through a leaf by means of non-polarisable electrodes at right angles to its surface, the electrodes, as in certain polarisation experiments in muscle, serving simultaneously to lead off to the galvanometer, there is always, if the galvanometer circuit is closed immediately after opening the exciting circuit, an ingoing after-current in the leaf, directed from above downwards, whatever the direction of the polarising current. An exciting current homodromous with the after-current is, however, much more effective, other conditions being uniform.

Burdon-Sanderson used a specially constructed rheotome for these experiments, which made only three revolutions in the minute, and thus closed the polarising current once in 20 sec. for $\frac{1}{10}$ to $\frac{4}{10}$ sec.; after an interval of $\frac{1}{10}$ sec. the galvanometer circuit was closed for $\frac{1}{10}$ sec. and the effect was noted.

"If the polarising current is comparatively weak, the after-effect gradually diminishes, and disappears in a few seconds. But if somewhat stronger currents are employed, the after-effect will only partially disappear, leaving a permanent alteration (modification) in the electromotive response of the leaf." With repeated closure of the polarising current at regular intervals of about 20 sec., the modified state is very quickly developed, and reaches considerable proportions. "In one leaf, *e.g.*, the lower surface was negative to the upper (P.D. = 140 degrees of compensator) before the passage of the current; four excitations reduced the P.D. to zero, after which the lower surface subsequently became positive to the upper, and each excitation by the current increased the effect, until it reached 320 degrees of the compensator."

As in muscle, secondary electromotive manifestations appear as galvanic indications of the action of the polarising current, independent of visible signs of activity, so here Burdon-Sanderson observed a modification, with currents so weak that their "make" produced no trace of excitatory reaction after closure. The "modification" then remained local, and was not transmitted further, so that a lobe or part of the same can be affected

without involving the surrounding tissue. In this respect again we are reminded of the polar after-currents in muscle.

It thus becomes intelligible that, according to the situation of the leading-off points on the opposite surfaces of a partially "modified" leaf, the excitatory variations discharged by a transmitted excitation may be directly opposite in character, the diphasic variation in the modified tract presenting different signs from that in the tract that is unmodified (normal).

Munk, as we have seen, assumed the precise seat of the excitation on the leaf of *Dionæa* to be without significance to the character of the electrical variation discharged, and concluded that the propagation of the changes which underlie the excitatory effect (movement) must be so rapid that they begin, as it were, simultaneously at all points. Burdon-Sanderson's investigations show that this theory (which is *a priori* improbable if the excitatory movements of plants correspond with the *excitation* of protoplasmic parts) is as a fact inadequate. It is evident that if the view advanced by Munk were correct, there should be no galvanic effect of excitation with a symmetrical lead-off from upper or under surface of both lobes, even when one side only was stimulated (Fig. 147). A variation under these conditions is only to be expected when the activity of the two lobes differs either in degree, or in the moment of its commencement; much as an electrical P.D. can only occur between two points of a muscle when the physiological state of the two points is different, or when the same state is developed in them at different times.

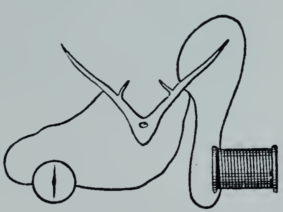

FIG. 147.

And we find experimentally that this method of leading off is invariably followed by galvanic effects of excitation, as appears at once from the curves, Fig. 148, *a*, *b*.

Fig. 147 represents a leaf led off symmetrically from the under surface, and excited with opening shocks. The galvanometer is replaced by a capillary electrometer, the effects being photographically recorded. The directly excited lobe is invariably at first negative, and subsequently positive to the other, giving rise to a diphasic variation similar in character to that which results on leading off two points from the normally isoelectric

surface of the ventricle. The galvanometer, of course, shows the same thing with the rheotome method.

In order rightly to interpret this "diphasic action current," it is essential to determine the rate at which the excitation (? the effect of stimulus) spreads in the parenchyma of the leaf.

Burdon-Sanderson used a pendulum rheotome for this purpose, with which it is easy to determine the time between the moment of excitation and commencement of the consequent electrical variation of the leaf-current. This current was, as before, led off from the middle of the opposite surfaces of a lamina. In a preliminary series of experiments, the exciting electrodes were placed on either side of a leading-off electrode on the upper

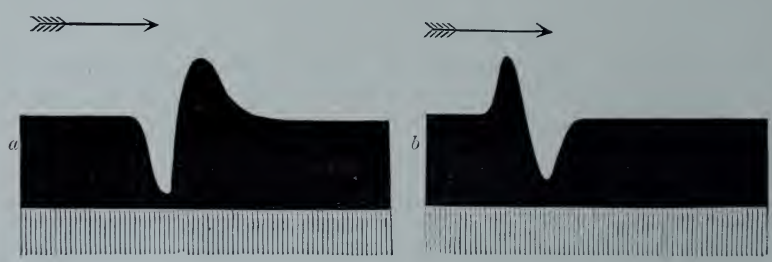

FIG. 148.

surface of a leaf, so that a straight line connecting the two passed through the leading-off contact. The first perceptible trace of phase I. of the excitatory variation generally appeared 0·041 sec. after the moment of excitation. If time is required for the spread of the excitatory activity, it is evident that the "latent period" must be very much longer (with unaltered position of the leading-off electrodes) when the stimulus is applied to the lobe that is not led off. That this is so appears from Burdon-Sanderson's experiments, where the interval between excitation and beginning of the variation as a rule exceeds 0·073 sec. Accordingly, if we estimate the distance between the two points excited in succession at 6 mm., the transmission of excitation must occur at about 200 mm. per sec. (at a temperature of 30°–32° C. in air saturated with aqueous vapour). An even greater disparity between the latent periods in the two cases might have been expected, supposing that, as in muscle, there were no *perceptible* latent period in the

galvanic effects of excitation at the actual point excited. Yet an experiment, in which excitation and leading-off are absolutely simultaneous, would encounter almost insuperable difficulties, not the least being to determine exactly the real commencement of the variation.

Burdon-Sanderson's assumption that the electrical variation does not coincide with the beginning of excitation, may be met with the same arguments that were brought forward above, in discussing the relations between excitation and contraction in muscle. If the galvanic alteration is really the expression of the chemical change induced by the stimulus, it must commence simultaneously with it, *i.e.* at the moment when the stimulus takes effect.

The preceding observations show beyond doubt that the primary phase of the excitatory variation accompanies and is the direct consequence of *excitation of the protoplasm of the excitable parenchyma cells of the leaf*—comparable throughout its manifestation with the galvanic effects of excitation in excitable *animal tissues, i.e.* the negative variation of muscle, nerve, or gland currents. It is therefore to be expected that the time-relations between the galvanic and mechanical effects in the leaf of *Dionæa* would be similar to those exhibited in muscle—always remembering the different causes of movement in the two cases.

In the first place it is evident that the excitatory variations of the "current of rest" are quite independent of the coarsely perceptible movements of the lobe, and are demonstrable both on the fixed and open leaf, and on that which is entirely closed. The next point, as Burdon - Sanderson has correctly pointed out, is to ascertain "whether the interstitial movement of the fluid discharged from the cells on excitation (which in all excitable plant-organs is the active cause of the change of form) may not occur without any perceptible change in the curving of the lobe, no matter how fine the means of observation employed." This entails the presumption that every excitation implying an electrical alteration must also cause a perceptible discharge of water from the excited cells. That there is further a perceptible interval between the moment of excitation and the consequent closure of the leaf of *Dionæa* may as a rule be verified from direct observation, since, when the temperature is not too high, the mechanical latent period is actually macroscopic, *e.g.* at

20° C., about 1 sec. Under all circumstances the electrical variation long precedes the excitatory movement.

For more exact investigation two methods were employed by Burdon-Sanderson. In the first "a light straw lever was cemented to two of the marginal bristles of a lobe, the opposite lobe being fixed to a support. The lobe thus attached was mechanically excited in such a way that the time of the exciting impact was recorded on a horizontally-moving smoked plate below the curve drawn by the lever."

In the second method the leaf was fixed in the same way, but a small mirror was cemented to the lower surface of the free lobe, by means of which the image of a horizontal slit was thrown on to a vertical scale, so arranged that the movement of the lobe could be exactly measured.

The result showed that with a temperature of 15°–20° C. the closing movement of a lobe, consequent on a single adequate excitation, lasted 5–6 sec., occurring rapidly at first, and then with diminishing speed.

With a succession of very weak mechanical stimuli (gentle impact on one of the sensitive hairs), inadequate singly to produce complete closure of the leaf, Burdon-Sanderson observed an effect which to some extent recalled the "staircase" of direct muscular excitation, the mechanical effect of the movement in each successive stimulation being greater than in those that preceded it. This reaction must, however, be referred to the fact that the resistance of the cells of the upper surface of the leaf to the closing movement, due to turgor, diminishes with each new excitation. "The magnitude of each diminution of resistance produced by excitation grows with each repetition of the stimulus, until the leaf finally closes together" (Burdon-Sanderson).

It may be assumed as certain that galvanic excitatory manifestations, similar to those of *Dionæa*, are to be observed in the pulvini of the no less sensitive leaves of *Mimosa*. Unfortunately there are, so far, few observations on this point. Kunkel, who, as we have seen, found a strong "current of rest" in the cushion of the primary leaf-stalk, the bristle being positive to the upper surface of the joint, observed, with the capillary electrometer, a variation of this current (consisting of a number of alternating oscillations) at the moment when contact with the most excitable point of the lower circumference of the pulvinus

begins to produce a downward movement of the petiole. There is a rapid preliminary variation, which is soon exhausted, and is followed immediately by a much more pronounced deflection in the opposite direction. The mercury slowly returns from the extreme point of this last, and either reaches its resting-point or exhibits a variety of smaller and slower oscillations.

Kunkel was quite aware of the difficulties of interpreting these complicated excitatory variations from his own theory, and was "not disinclined to refer them to single phases of the active displacement of water." He derived the first rapid negative swing from "alterations" of the protoplasm, which disturb the diffusion-processes caused by the contact of the moist electrodes, and fundamental to the current of rest. The large positive deflection, on the contrary, "expresses the main displacement of water which results in the movement of the entire leaf; the (negative) return corresponds with the restitution of the organ to its earlier state." Yet, as Kunkel himself noticed, it must not be forgotten that in *Mimosa*, as in *Dionœa*, electrical variations can still be observed when, after repeated excitation, there is no longer any perceptible movement of the leaf, so that there can hardly be any considerable displacement of water.

If we endeavour, on the basis of these experiments on *Dionœa*, to form any picture of the possible causes of the difference in potential in the "resting" state and during artificial excitation, it is in the first place clear that the same principles which we have already accepted as determining the appearance of "cell currents" must hold good for vegetable as for animal cells. The only question is whether we are here justified, as in the uni- and multicellular animal glands, in regarding the single cells as individually electromotive, or whether this property is not rather attached to them solely in connection with other dissimilar elements, whether, *i.e.*, we are dealing with electromotive cells or cell-complexes. Munk notably tried to develop a theory from the first standpoint—albeit in a very different sense from electromotive activity of the isolated mucous cell. He held, as was stated above, that the poles of each cell were positive to its centre, and that after excitation the P.D. between the poles and the negative equatorial zone either declined (as in the upper layer of the parenchyma), or was augmented (cells of the lower surface). Seeing, however, that the structure of these cells

does not give the smallest support to such a purely gratuitous hypothesis, and that it fails, moreover, to account for the differences of potential which Burdon-Sanderson has shown to exist regularly between upper and under surface, we are thrown back on the scarcely less arbitrary assumption of a constant (chemical) difference, and resulting electrical P.D., between the upper and lower halves of each parenchyma cell on the upper surface of the leaf, comparable in some measure with the difference in potential between free end and base of the mucous cells. But it is obvious that neither structure nor arrangement of the single cells agrees with even this presumption. Burdon-Sanderson's view is undoubtedly the more probable, that the surface of a single cell is individually, and under all conditions, isoelectric. It is hardly necessary to add that no current can result from the mere contiguity of two cell-bodies surrounded with cellulose walls, and thus completely separated, when the one is altered equally in all its parts with respect to the other; any more than a muscle-current appears when a fibre that is equally active at all points is brought into contact with another fibre in the resting state. But whenever the bodies of adjacent cells are directly united by processes, and so form a physiological whole (*i.e.* continuity of substance), any chemical differences arising within the plasma of the cell-aggregate must produce current that can be led off externally.

Many investigations in recent years concur to show that the bodies of vegetable cells are frequently, and perhaps always, connected directly through their cellulose sheaths by means of fine processes, as also occurs in many animal tissues. If this may be assumed of the cells in the *Dionæa* leaf (it has been directly proved for the cells of the excitable cushion of *Mimosa* by Gardiner and Haberlandt), and if the same continuity exists between the excitable plasma of the upper and the non-excitable plasma of the lower parenchyma cells, then all the electrical manifestations so far described may be referred to differences of potential between upper and lower cells, which are not merely contiguous, but are in direct protoplasmic connection, and happen to be in unlike and varying physiological states.

From this point of view it would not be without interest to test the electromotive reactions of vegetable organs in other cases where chemical differences between different layers of cells might

be expected, *e.g.* in the numerous examples of permanent differences in turgor (growing fruits, motor organs of bean, etc.).

The glandular parts of plants should also be suitable objects. Biedermann found in various species of *Drosera* that on leading off from the stalk on one side, and the surface of the leaf, which is thickly set with little glands, on the other, there were considerable differences of potential.

The intrinsic nature of the physiological changes of state which underlie the galvanic effects of excitation in the excitable leaf of *Dionœa*, or pulvinus of *Mimosa*, cannot with our present knowledge be pronounced upon, any more than in the corresponding electromotive activities of animal mucous cells. The wide-reaching analogies in the two cases can hardly be overlooked, as emphasised by Prof. Burdon-Sanderson, who has been good enough to make especial communications on this subject. As in the tongue of the frog, so in the leaf of *Dionœa*, we find a "current of rest," of which the sign may alter with circumstances, its internal relations with the galvanic excitatory effects being invariable and unmistakable. In both cases, moreover, the effect of excitation is a frequently diphasic variation, the sign of which depends throughout on the state of the organ at the moment. Burdon-Sanderson therefore holds it to be not improbable that in the leaf of *Dionœa*, as in animal mucosæ, the current led off may be the result of two antagonistic chemical processes which occur in the plasma of the cells, and are always simultaneously present. These imply the development of an opposite potential, while to one of them is due the permeability of the cell-wall to water.

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CHAPTER VII

STRUCTURE AND ORGANISATION OF NERVE

In nerve, as in muscle, function and all essentially physiological properties are so bound up with the finer structure of the individual elements that it is desirable to give some account of the latter. We need only consider the *conductors, the nerve-fibres,* since all existing observations on electrical excitation and electromotive action relate almost entirely to these. The nervous system belongs exclusively to the animal organisation, and indeed to the more highly developed Metazoa only. Plants, unicellular animals, and the lower Metazoa have no nerves, and if in exceptional cases (as in the excitatory movements of many plants) there are forms of activity which resemble the vital manifestations of the animal organisation as effected by nerves, it is easy to prove that the resemblance is merely superficial.

In the animal organism, communication between distant organs or groups of organs is generally effected in two ways: first, by the circulation of the nutritive fluids; second, by the nervous system. The former may be said to act as the more sluggish transport; materials prepared or taken up in the organ are carried farther, to be profitably assimilated, or excreted. In opposition to this sluggish medium we have the marvellously rapid communication between remotest parts, which is brought about by the nervous system. The mode of action within the nerves has often been compared to that of the telegraph system, and so long as we bear in mind that what is transmitted in the nerve is *not* electricity, the comparison is a very fair one. With regard to this last point the most extravagant conceptions prevailed, long before the discovery of the fundamental phenomena of electro-physiology, and

the key to nervous activity was always looked for in electrical manifestations. But as in muscle, so in nerve, these hopes were not to be realised in their original sense, and although Albrecht (1) has recently attempted to revive the old doctrine of the identity of the "nervous principle" with current electricity, there can be no serious discussion on these lines. In nerve, as in muscle, electromotive action must be viewed as the concomitant of chemical processes, while—again as in muscle—its proper significance is not yet adequately established. The nervous system invariably consists of cellular elements (ganglion- or nerve-cells) and of fibres, which must be reckoned as processes of the former, so that the cell with its fibre forms an anatomical and physiological unit ("*Neuron*," Waldeyer; "*Neurodendron*," Kölliker). At their first appearance, both phylogenetically and ontogenetically, the nerve-fibres are pale fibrous structures, greater or less in length, which always spring from special cell-bodies (ganglion-cells), and either pass branched or unbranched into the peripheral end-organs, or establish mutual communication between different ganglion-cells. While in the lower forms of animals this condition is permanent, it is only a temporary phase of development in the higher species, since various sheaths are added later (in parts at least) to the originally naked fibres, so that the structure of the individual nerve-fibre may become very complicated. The fibres may be classified into different groups according to the very different properties of these sheaths or investments, the most characteristic being those termed *medullated* and *non-medullated* fibres. The nervous system of vertebrates is composed almost exclusively of the former, while the latter predominate among invertebrates and the lowest vertebrata.

Hence we may conclude that *the one essential constituent of a nerve-fibre is, functionally speaking, the substance of the cell process*—or "*axis-cylinder*," as it is termed from the sheath which usually envelops it, and serves mainly as a protective covering. We shall, therefore, understand by "*nerve-fibre*" the single axis-cylinder, whether as the process of a central or peripheral ganglion-cell, or as the branch of such a process; irrespective of its being *per se* naked, or enclosed in a sheath, or if the same sheath encloses few or many axis-cylinders. The last case occurs most frequently in invertebrates. The nerves of the proboscis of many Nemertines, *e.g.*, contain within a tolerably thick

nucleated sheath of connective tissue a whole bundle of the finest axis-cylinders, each springing from one nerve-cell (2). On hastily examining preparations stained *intra vitam* with methylene blue, such a bundle of fibres might easily be taken for a single nerve-fibre with one axis-cylinder and a thick sheath; closer inspection, however, shows the central filament to be composed of excessively fine fibres, deeply stained, and all doubt as to their nature is removed by the connection in every case with a separate nerve-cell (Fig. 149). The term "nerve-fibre" must, therefore, only be applied to the minute fibrils which branch off from the central bundle of the nerve-trunk to supply the peripheral end-organs.

Fig. 149.—Section of a nerve from the proboscis of *Amphiporus marmoratus* with paired cells. (Methylene-blue preparation from O. Bürger.)

While in this case the relations of calibre between the single fibres which constitute the bundle are tolerably uniform, we elsewhere find marked differences. In insects and crustacea, *e.g.*, broad band-shaped axis-cylinders frequently run alongside very small and fibril-like filaments in the same sheath, and this not merely in the coarser nerve-trunks, but in the finest terminal branches also, where the calibre would justify us in reckoning them individually as nerve-fibres. But it is in these muscular nerves of Arthropoda with their copious ramifications (*e.g.* in the familiar instance of the crayfish), that it is most easy to show that no essential difference in structure exists between the coarser and finer branches of the nerve, apart from the number of axis-cylinders contained within one sheath of connective tissue. Neither the one nor the other must be designated as *nerve-fibres*, but must be treated simply as *bundles*. Notwithstanding therefore that, even in the minutest ramifications, and actual terminal branches, there may be several axis-cylinders in a common sheath, the morphological definition of a nerve-fibre must be strictly confined to one such axis-cylinder. It follows that the richly developed connective-tissue sheath of the finest nerve-branches in invertebrates must not be regarded as analogous to the

"sheath of Schwann," but is rather comparable with the connective tissue ("endoperineurium") which, in vertebrates, unites the axis-cylinders, along with their special sheaths, into primitive bundles of fibres, or nerve-trunks. Only that fine, homogeneous, nucleated sheath which partially invests the peripheral axis-cylinders (medullated and non-medullated) of vertebrates and some invertebrates is to be termed the sheath of Schwann.

In the muscular nerve of crayfish, the neural sheath, both in the larger trunks and in parts where the axis-cylinders run singly, exhibits, even in the fresh state, and still more after treatment with the gold method, an obvious stratification, resembling in places the highly developed and richly nucleated connective-tissue sheath on the capsule of the Pacinian corpuscle (Fig. 150). A similar concentric layering appears in the neural sheath of several Orthoptera (locusts). In other cases, on the contrary (*e.g.* many

FIG. 150.—Isolated muscular nerve from the abductor muscle of crayfish. (Gold and formic acid.)

insects), the substance in which the axis-cylinder is embedded is finely granulated, like protoplasm (3).

These relations between the nerve-fibres (axis-cylinders) of invertebrates and their sheaths only appear fully on staining the former by proper methods. The gold method, which was so much employed, after Cohnheim, has been superseded by the methylene-blue method of Ehrlich, more particularly for invertebrate animals. Biedermann has failed to determine a special and individual sheath within the common integument of the finer axis-cylinders of invertebrate nerves, unless the compacter layers of connective tissue immediately surrounding each axis-cylinder in the muscular nerve-trunk of the crayfish be recognised as such. As a rule, invertebrate nerves present a naked axis-cylinder within a common sheath, or substratum of connective tissue, which is histologically distinct from the specific sheaths of the nerve-fibres of higher animals, even when it invests a single axis-cylinder. In vertebrates, similar

but coarser sheaths of connective tissue surrounding a single axis-cylinder appear exceptionally.

Thus the nerve-fibres of the electrical organ of *Torpedo* exhibit a tolerably thick sheath, and an extreme development of the same, consisting of many concentric layers closely packed together, is also characteristic of the two giant nerve-fibres which supply the electrical organ of *Malapterurus*. These nerves are as thick as a sewing-needle, and yet contain only a single medullated primitive fibre.

The sheath of Schwann and the medullary sheath are the only "specific" sheaths of nerve-fibres. As we have stated, a true sheath of Schwann rarely appears in the nerve-fibres of invertebrates, and then only in cases where there is a comparatively broad axis-cylinder. In nearly all crayfish nerves, if not excessively fine, there are, along with a number of very delicate axis-cylinders which never exhibit a special sheath, others of much greater diameter; these, on treatment with methylene blue, for the most part become paler in colour, and exhibit, in Remak's words, a visible "tubular" structure, *i.e.* a delicate, apparently structureless, nucleated sheath with its content, the axis-cylinder proper, to the finer structure of which we shall return later.

FIG. 151.—A peripheral bundle of the human sympathetic nerve, fixed with osmic acid. Two medullated fibres (*mF*) lie in a bundle of Remak's fibres. Epineural sheath beyond. (Schiefferdecker.)

These structural relations of invertebrate nerves have much in common with the fine nerve-trunks found in the sympathetic system of vertebrates, which contain a bundle of non-medullated fibres (axis-cylinders)—the gray fibres of Remak—within a strong sheath of connective tissue (epineural sheath), Fig. 151. Each of these fibres appears when isolated as a transparent flattish band—homogeneous, or with delicate longitudinal striations, in the fresh state, with here and there a long oval nucleus. M. Schultze

described Remak's fibres as axis-cylinders with a sheath of Schwann, and they have since been very variously interpreted. It was even questioned whether they were nerves at all, but later on Schultze's opinion was very generally adopted. Remak observed that the fibres, which he described as naked, "and nearly always longitudinally striated on the surface," were readily decomposed into the "finest threads," and in fact nothing could be easier than to demonstrate this in suitable preparations, *e.g.* the splenic nerves of ruminants. Kölliker and Schiefferdecker (4), on the other hand, regarded each Remak's fibre as "a bundle of fine axis-cylinders, surrounded by a more or less complete sheath of Schwann." The question again can only be determined by reference to the origin of the fibres involved. If it can be shown that a "Remak's fibre" originates as a *simple* fibre, and that its individual "elementary fibrils" are not independent cell processes, there can then be no doubt that it represents a single axis-cylinder (nerve-fibre), and not a bundle of such fibres. It has long been known that broad prolongations spring from the sympathetic ganglion-cells, which are invested with a complete sheath of Schwann; and these, in their turn clothed with a process of the cell sheath, correspond throughout with Remak's fibres. These last, in continuing their course (notwithstanding the inequalities of the cellular sheath as first remarked by Ranvier), make good their existence as special structural elements, which are easily isolated—like the medullated nerve-fibres; while the elementary fibrils ("Remak's fibrils," Kölliker) cling together much more closely, and can only be isolated in places. It is, however, easy to demonstrate their existence, both in teased preparations, and at the cross-sections of large nerve-trunks containing Remak's fibres (splenic nerves of the ox).

The elements of the olfactory nerve are similar in structure to Remak's fibres. As shown by M. Schultze, the peripheral expansion of this nerve consists in all vertebrates of non-medullated elements, which, *e.g.* in the pike, are clearly defined, and surrounded by a tolerably thick structureless sheath, regarded by Schultze as the sheath of Schwann. The single fibres, some 10–40 μ in diameter, are round, or polygonal from pressure in cross-section. The content of the sheath exhibits a somewhat faint longitudinal striation even in the fresh state. After prolonged maceration in 0·04 % chromic acid, or 0·4–0·6 %

solution of potassium chromate, Schultze succeeded in isolating two kinds of elements from the nerve-fibres, *i.e.* countless minute fibrils, and a finely-granulated mass, "of which it is hard to say whether it forms part of the little fibres or lies between them." This is the characteristic structure of the olfactory fibres; and here we have the first mention of a *fibrillated* structure of nerve-fibre, which became the starting-point for the further investigations by which Schultze established the doctrine of fibrillated structure for all nerve-fibres. Regarding the axis-cylinder of medullated nerves as a bundle of the finest fibrils with granulated interfibrillar substance, he compared it with the fibrous elements of the olfactory nerves, and defined the latter as "axis-cylinders with a sheath of Schwann."

Babuchin objected to Schultze's theory, and declined to recognise the sheathed "nerve-fibres" which Schultze isolated from the olfactorius as comparable with the fibres of Remak. Even if the comparison is legitimate in many animals, it may be shown in other cases that the supposed sheath of Schwann corresponds better morphologically with the perineurium of the nerve-trunks. Fine transverse sections of the olfactorius (of pike) show that secondary septa run out from the external sheath of the large nerve "fibres" (in Schultze's sense), and divide the fibre into two or more compartments. In the higher vertebrates, on the contrary, there is no such marking out of single "fibres" by special sheaths. Boveri, at any rate, has failed to find nucleated membranes, either by isolation or in cross-section. "An arrangement of larger or smaller irregular groups is indeed easily identified at the transverse section, but they are not separated by sharp double lines, as would be the case with membranes investing distinct partitions. The dividing line is single, often obscure, and dotted in appearance, in no way comparable with the secondary sheaths of the pike's fibres." Boveri, therefore, assumes correctly that these partition walls are "a superficial expansion of connective tissue, such as are also found between the fibres of the white matter of the spinal cord." This is borne out by the position of the nuclei. "It is clear from the 'fibres' of vertebrates higher than fishes that the nuclei lie not only between but also inside them."

The spaces within these septa are seen in cross-section to be filled with a gray reticulum (the interfibrillar substance of Schultze), in the meshes of which dotted sections of minute fibrils appear,

with a proper stain, as in the transverse sections of Remak's fibres. But while, from their origin, each of the latter must be regarded as a *single* axis-cylinder, we are from the same reason compelled to accept each of the fine elementary fibres, or fibrils, within the common sheath of the olfactorius as being in itself a nerve-fibre or axis-cylinder. The peculiar relations of the olfactory fibres to certain spherical structures of the olfactory bulb have long been known, but it is only with the help of recent methods of staining that an explanation of them has become possible.

It is now known that two processes run out from the spindle-shaped body of each "olfactory cell"—one short and directed towards the mucous surface, interpolated between the remaining epithelial cells; the other, long, fine, and filiform, extending as an olfactory fibre towards the bulb, to end there in a "glomerulus." A number of these extremely fine nerve-fibres are gathered up into coarser bundles (olfactory bundles), which, after a shorter or longer course, pass out of the olfactory mucosa into the olfactory bulb, through the cribriform plate of the ethmoid, and enter the layer of glomeruli. The individual fibres, which are undivided and often varicose, remain of the same breadth throughout their passage from olfactory cell to glomerulus. The fibres begin to branch shortly before entering the glomerulus; they divide dichotomously several times, and traverse the glomerulus by a somewhat complicated path, until they end freely (5). Often, as described by Ramón y Cajal, Van Gehuchten, and Martin, as well as by Kölliker, "not merely one, but two, three, or several fibres, enter one glomerulus. They all pursue the same course, branching freely (dichotomously) in the glomerulus, and interlacing without anastomosis." These terminal ramifications of the olfactory fibres in the glomerulus therefore represent the central endings of the fibres, and in spite of their fine structure they cannot be regarded otherwise than as independent nerve-fibres (axis-cylinders). Each olfactory fibre, or more correctly fibril, thus corresponds with the centripetal process of an "olfactory cell" in the epithelium of the olfactory mucous membrane. The branches of these fibres in the glomerulus interlace, without anastomosing, with other fibres that arise from bifurcation of the processes from the ganglion-cells (prolongations of the so-called "mitral cells").

If these excessively fine elements of the olfactory nerve, which resemble the "fibrils" of Remak's fibres in structure and appearance, are thus independent and non-medullated fibres, they represent in some degree the lowest and least developed form of nervous tissue. Remak's fibres are higher in the scale, since they present bundles of fibrils, which possess (even if incompletely) a sheath of Schwann: while the most developed non-medullated fibres again appear as an axis-cylinder completely surrounded with a sheath of Schwann, as, typically, in the peripheral nerves of the lower, and even, at a certain developmental stage, of the higher vertebrates (*Petromyzon*, *Amphioxus*, *Cyclostoma*). The axis-cylinder, to the finer structure of which we shall return later, is here immediately surrounded on all sides by the sheath of Schwann. This is tubular and transparent, and betrays its cellular formation only in the presence of long nuclei upon the inner surface; the upper surface is often invested with a delicate membrane of fibrillated connective tissue ("Henle's sheath"), which may be regarded as part of the connective tissue (perineurium) that binds a number of fibres into a nerve-trunk (Fig. 152).

FIG. 152. — Fibre from trigeminal nerve of *Petromyzon fluviatilis* treated with Müller's fluid. (Schiefferdecker.)

All nerves consisting of these kinds of elements differ essentially, even to the unaided eye, from those composed exclusively, or in great part, of medullated fibres, the complicated structure of which will be described below. Non-medullated nerves, in consequence of the transparency of the single fibres and their investment, are always clear, and grayish in colour, and often, especially in invertebrates, of an almost gelatinous consistency. Medullated nerves, on the other hand, are much more compact and resistant, and are characterised by their ivory whiteness and opaqueness. This is due to the optical properties of the *medullary sheath*, the finer structure of which has long occupied the attention of histologists.

If a medullated nerve-fibre is examined in the living tissue, or immediately after isolation in an indifferent fluid, it appears as a highly refractive, transparent, and perfectly homogeneous

thread, with a simple contour, which is constricted here and there at irregular intervals, known after their discoverer as nodes of Ranvier ("*étranglements annulaires*") (Figs. 152, 153). The length of segment between the nodes is considerably greater in the inferior vertebrates (fish, amphibia) than in the higher, so that in the former there are fewer nodes in the same tract; corresponding perhaps with varying consumption of materials, if, as Ranvier believes, the nodes are to be regarded as points of entrance for the nutritive fluids. It may also be remarked that the electrical nerves of *Torpedo*, as well as embryonic nerves, have invariably shorter and more numerous segments than fully-developed fibres. Ranvier's nodes, again, are found at all dividing points of peripheral medullated nerve-fibres, while in the central elements their existence is doubtful. Near the constrictions, in fresh, peripheral, medullated fibres, are the long nuclei of the sheath of Schwann, which lie at the side of the fibres, and seem to be embedded in the medullary sheath. The fact that (in higher vertebrates) *one* nucleus is placed centrally between each pair of nodes has, along with other facts (*infra*), given rise to the view that each nerve-fibre is due to the fusion of several cells, a theory which can hardly be maintained in the face of embryological researches. In the lower vertebrates (fishes) there are several nuclei (5–18, according to Key and Retzius) in each segment. In their finer structure the nuclei of Schwann correspond essentially with other cell-nuclei. While the sheath of Schwann forms a complete tube, investing the fibre closely on all sides, and surrounding the axis-cylinder even at the nodes of Ranvier, where the medullary sheath is interrupted (*infra*), the latter exhibits segmentation apart from the constrictions of Ranvier. After death, the double contour of the medullary sheath is interrupted by oblique lines on either side of the nodes of Ranvier, which give the appearance of longer or shorter segments of medulla, fitting together with funnel-shaped

FIG. 153.—Nerve-cell with branching process from the spinal ganglion of rabbit. (Schiefferdecker.)

ends: the internal relations of these were specially investigated by Schiefferdecker. These secondary breaks in the continuity of the medullary sheath are known, after their discoverer, Lantermann, as "Lantermann's indentations" (Fig. 157). On treating fresh medullated nerve-fibres with silver nitrate, characteristic black crosses appear at the constrictions; the solution of silver enters most rapidly at this point, and not only colours the ground-substance of the constriction (Schiefferdecker's *Zwischenscheibe*—intermediary discs), but also penetrates a certain distance along the axis-cylinder, spreading on either side between the latter and the medullary sheath ("periaxial clefts") (Fig. 159). The long arms of the cross are often discontinuous, and appear as a more or less prolonged series of transverse striæ, the so-called "silver lines of Frommann," the origin of which has not yet been adequately determined.

During the death of the fibre many striking phenomena make their appearance. We have said that the medullary sheath in living nerve-fibre is smooth and homogeneous: in moribund nerve it alters conspicuously. Even with the most favourable conditions, in fluids that are as far as possible indifferent, the excessive instability of the substance of the medullary sheath causes rapid alterations, which are generally described as coagulation-phenomena, or formation of "myelin figures." These are chiefly characterised by a kind of folding and wrinkling of the medullary sheath, so that the lateral border of the fibres, which was at first rectilinear, becomes much undulated, while irregular lumps and knotty lines and networks appear on the surface, and soon conceal the notches, although the constrictions still remain visible.

These changes are intimately associated with the chemical constitution of the medullary sheath, lecithin and cholesterin being among its chief constituents. It is owing to the former that the medulla of the nerve, when treated with osmic acid, stains a more or less deep black, so that even the finest medullary sheaths can be detected by this reaction. Water, dilute acids, and solutions of salts cause a swelling of the medulla, which occurs most rapidly and distinctly in the central nerve-fibres, where the sheath of Schwann is wanting. Here, as also in the peripheral medullated fibres, there is often a characteristic blistering of the medullary sheath, beginning at the free end of the medullary segment, and extending right along it.

This swelling of the medullary sheath is naturally most obvious at points where, *e.g.* at a cross section, the myelin is in immediate contact with the entering fluid. Here, along with the formation of characteristic "myelin figures," there is often a regular outflow of medulla from the sheath, which may extend far beyond the cross-section. Very singular figures are produced by treating medullated nerve-fibres with hot alcohol and ether, when a great part of the medullary substance goes into solution, leaving a delicate network of a highly refractile substance, which gives a chemical reaction analogous with that of keratin, and therefore termed *neurokeratin* by Kühne and Ewald (Fig. 154). It is not known whether these reticulate "horny sheaths" are preformed as such within the normal medullary sheath. All changes produced in the aspect of medullated nerve-fibres by different reagents must be accepted with great caution as to structural conclusions, owing to the extreme instability of the medullary sheath.

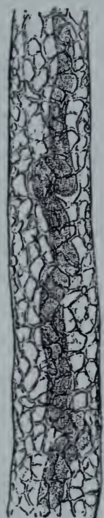

Fig. 154.—Nerve-fibre of frog boiled in alcohol. In the centre is the twisted axis-cylinder; between this and the sheath of Schwann the network of neurokeratin. (Kölliker.)

We said that all medullated fibres of vertebrates are at first destitute of a medullary sheath, which only appears at a given stage of development. How this occurs, and how the nerve-fibres themselves are developed, is a disputed matter. It is certain that nerve-fibres arise under all circumstances from special cells (nerve-cells), and must be regarded as their prolongations; this Kölliker and His have established for the roots of the spinal nerves also. Both anterior and posterior roots at first appear as bundles of naked axis-cylinders, springing in the former from the motor cells of the anterior horn, while in the posterior roots some of the fibres run inwards from the cells of the spinal ganglia to the cord, and some outwards to the periphery. Later on, the cells which arise from the mesoblast form first a sheath which invests the entire bundle of unmedullated fibres, and subsequently a special sheath to each fibre (sheath of Schwann). This secondary origin of the sheath of Schwann appears still more plainly in the developing nerves of the tadpole's tail

(Kölliker, Rouget, Hensen). Hensen found that these nerves at first consisted of fine shining forked threads without nuclei; later on single nuclei appeared, at first near the body-axis, and subsequently in the terminal ramifications also. These cells undoubtedly belong to the connective substance, from the fusion of which arises the sheath of Schwann. Neither medullary sheath nor sheath of Schwann appears to develop continuously at all points along a nerve-fibre.

It is known that in the central nervous system (brain and cord) the fibres of the pyramidal tract become gradually invested with medullary sheaths, in the direction from parent cells to spinal cord, and the same is stated by Kölliker of peripheral nerves, where the development of medulla is directed from trunk to periphery. Kölliker disputes the assumption of Hensen that the medulla originates in the form of single drops, since he observed on the tadpole "that it appeared *ab initio* as a coherent

FIG. 155.—Two medullated nerve-fibres of *Palaemon squilla*. (Retzius.)

tube, which gradually acquired the dark contour, the transition from pale to dark-walled fibres being thus imperceptible." This seems to occur first near the nuclei of Schwann, so that medullary segments are formed, separated by longer non-medullated tracts corresponding with the constrictions of Ranvier.

The presence of true medullary sheaths in certain nerves of invertebrates has frequently been asserted, but is under all circumstances a rare occurrence. Without entering into the older researches, we may quote the investigations of Retzius on *Palaemon squilla*, and of Friedländer in Annelids (*Mastobranchus, Lumbricus*), as proving the existence of medullated nerve-fibres in invertebrates.

The nerve-fibres of *Palaemon* present the most exact structural conformity with the medullated nerves of vertebrates. In these, Retzius was able by the silver method, and also by methylene blue, to show characteristic figures corresponding with Ranvier's crosses, as well as Frommann's lines, corresponding with the constrictions, and appearing at definite and regularly recurring intervals (Fig. 155). Between the nodes there is a long oval

nucleus, which obviously corresponds with Schwann's nuclei in medullated vertebrate nerves, although Retzius disputes the existence of the sheath of Schwann, not merely in the splanchnic cord, but also in peripheral nerves. The myelin sheath runs uninterruptedly from one constriction to the next, exhibits double contours, and a shining, fatty appearance; after treatment with osmic acid the sheath becomes first gray, then black, exactly like the medullary sheath of vertebrate nerve-fibres (6).

The Axis-Cylinder

The finer structure of this, the functionally most important part of the nerve-fibre, is again much disputed. Apart from the undoubted difficulties of investigation, there is no doubt that the most appropriate objects have not in many cases been selected for experiment. On the one hand large elements are required, on the other absence of thick sheaths which may obscure the field of the microscope. It is *a priori* obvious that medullated fibres must be less favourable objects than the non-medullated fibres of vertebrates and invertebrates. And, in fact, that theory of the structure of the axis-cylinder which is most widely current, and appears morphologically and physiologically the best-grounded, is fundamentally derived from observations on the nerve-fibres of invertebrate, and non-medullated fibres of vertebrate animals. As early as 1843 Remak noted a bundle of fine fibrils in certain giant nerve-fibres of the ventral cord of the crayfish, in place of the axis-cylinder, and M. Schultze subsequently embraced the view of a uniform fibrillated structure of the axis-cylinder in all nerve-fibres. He pointed out that (more especially in the thick medullated fibres from the lateral columns of the spinal cord, "in which, since there is no sheath of Schwann, the axis-cylinder can be readily isolated, either in the fresh state, or still better after maceration in iodised serum") a parallel striation and a finely-granulated substance between the striæ may be distinguished with a high power, which can only indicate "a composition of fibrils and interfibrillar substance." Even within the medullary sheath, Schultze was able to detect the same structure of axis-cylinder in the thick fibres from the brain of the torpedo. Very significant again for the fibrillated structure of the axis-cylinder are the

various observations on its origin from the corresponding cells, made by M. Schultze on the large nerve-cells of the spinal cord and brain in vertebrates, and by Hans Schulze with even greater success on invertebrates. In both cases the bodies of the ganglion-cells also showed a more or less definite fibrillated structure, which was most obvious in the cortex. This was the more easy to recognise since adjacent fibrils were separated by comparatively thick layers of plasmatic ground-substance. The complicated course of the single small fibres within the cell appeared, according to M. Schultze, with special clearness in certain conspicuous multipolar ganglion-cells in the brain of the torpedo, where it is easy to recognise that the fibrils partly radiate in different directions from each process into the body of the cell, and partly describe concentric circles round the central nucleus. Any doubt as to the pre-existence of a fibrillated structure of the axis-cylinder was finally removed by the investigation of the broad non-medullated nerve-fibres of *Petromyzon*, which are even better adapted than certain fibres of invertebrates (*e.g.* crayfish) to demonstrate these structural relations in the living preparation (Schiefferdecker, 7). Within the sheath of Schwann two substances may usually be recognised: (*a*) a bundle of the finest fibres situated in the axis (nerve-fibrils, axis-fibrils), which often exhibit an undulating course, and are closely invested with (*b*) a homogeneous substance, which no doubt penetrates into the interior of the "axial filament," as Schiefferdecker named the bundle of fibrils—and there separates the single fibrils, some 0·4 μ thick (Fig. 152). There is between the latter and the homogeneous ground-substance (Kölliker's *neuroplasm*, "*axoplasma*") a similar relation to that in smooth and striated muscle-fibres between contractile fibrils and sarcoplasm. The layer of axoplasm is best developed in the thickest nerve-fibres, and forms a smaller constituent of the entire axis-cylinder in proportion as the fibres are more slender. This is plainly seen in transverse sections of hardened nerve-fibres (Fig. 156). The central bundle of fibrils seems to be almost equally developed in large and in small fibres, while the extent of the axoplasma varies considerably. "With decreasing diameter of axis-cylinder, the mass of axoplasm diminishes more rapidly in *Petromyzon* than the number of fibrils. Since these last are probably the true conducting substance, it is impossible in

Petromyzon to draw any direct conclusion at first hand from the diameter of the axis-cylinder as to bulk of conducting substance. The distance between two fibrils is always greater than the diameter of the fibrils; which are therefore separated by a comparatively large mass of axoplasm. The fibrils of *Petromyzon* are excessively unstable, and are visible only during life; as soon as they begin to die they break up, even when examined in the serum of the same animal, into fine granules of high refractile power, which at first lie in rows, corresponding with the fibrils of which they are the disintegration product. With advancing dissolution the axial bundle flows away in a viscid mass, along with the firmer substance of the axoplasma." The fibrils appear less capable of resistance than the axoplasm. "Shortly after death nothing remains of the fibrils; in their place there is a knotty string, which has often been figured." (Schiefferdecker's words, thus quoted, are confirmed by the observations of Biedermann.)

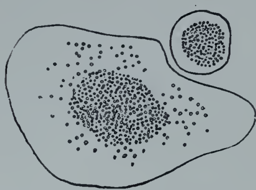

Fig. 156.—T.S. of axis-cylinders from trigeminal nerve of *Petromyzon fluviatilis*. (Schiefferdecker.)

It is far more difficult to discover the structure of the axis-cylinder in the nerve-fibres of the higher vertebrates, which are surrounded with a thick medullary sheath; and this no doubt accounts for the current divergences of opinion. We should *a priori* assume that the structural relations of the axis-cylinder would coincide in all essential points throughout the animal kingdom. When the existence of a fibrillated structure has been determined in one case, it may almost be postulated that fibrils are everywhere the proper constituents of the cylinder-axis. And this presumption of Remak and Max Schultze has in fact been confirmed by the remarks of Engelmann, Kupffer, Maley, Boveri, Kölliker, Jacobi, Joseph, and others—neither v. Fleischl's theory, that the axis-cylinder is a column of fluid, nor that of Kuhnt, that the axial space is filled with "a soft, somewhat elastic, homogeneous mass, finely or coarsely granulated," and that the fibrillar longitudinal striæ are folds of the supposed "axis-cylinder sheath," having any foundation.

As in the non-medullated fibres of *Petromyzon* and certain invertebrates (crayfish), so in medullated fibres, the axis-cylinder is composed of a soft ground-substance rich in water, and of

apparently gelatinous consistency (the "axoplasma"), and the fibrils embedded in the same. But while in the above examples the fibrils constitute a central bundle, more or less thickly invested with axoplasma, in medullated fibres they are distributed equally over the entire section of the axis-cylinder, so that the investing layer fails to appear, and forms an insignificant marginal zone. With appropriate reagents (acid fuchsin, bismarck brown, etc.) the fibrils are distinct upon the longitudinal aspect of the fibres as well as at the cross-section. It then appears that the fibrils lie closer together and are united by less cement-substance at the constrictions, so that the axis-cylinder is most slender at these points (Fig. 157). Engelmann (8) argues in favour of a pre-

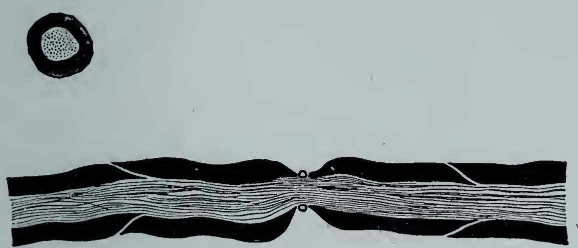

Fig. 157.—L. and T.S. of medullated nerve-fibre from frog's sciatic nerve (osmic acid, acid fuchsin). Nodes of Ranvier and two Lantermann's notches, fibrillar structure of axis-cylinder.

formed discontinuity of fibrils at the nodes, chiefly on the ground that the axis-cylinder under certain conditions exhibits a break in continuity at the point of constriction, "corresponding with the black cross-lines of the silver reaction" (Engelmann's *Querscheibe*). Engelmann's reasoning was subsequently rejected, and cannot therefore be cited in support of the view that the medullated nerve-fibre consists of single juxtaposed cells (*cf.* Jacobi, Boveri)—an assumption that is disproved by recent embryological observations. It may be remarked that Ehrlich's "intravital" methylene-blue method has never (in Biedermann's experience) brought out distinct traces of fibrillar structure in the axis-cylinder of fresh preparations, either in medullated or in non-medullated fibres; on the other hand, certain splanchnic fibres of *Hirudo medicinalis* stained by this method show, after treatment with picrate of ammonia, an unmistakable construction from single fibrils. It is still uncertain whether the axis-cylinder as a whole (fibrils + neuroplasm) may not, in addition to its

other investments (sheath of Schwann, medullary sheath), also possess a special delicate sheath ("axis-cylinder sheath"). In isolated cases this certainly appears to exist, always, however, as an excessively fine layer, hardly to be counted as a membrane proper.

The extreme instability of the substances of which the axis-cylinder consists, leads, when it is treated with reagents, to the appearance of many morphological changes which, without due precautions, might easily lead to fallacies. Such is the marked wrinkling induced even by physiological salt solution, and still more by all strongly dehydrating methods of hardening, such as alcohol, chromic acid and its salts, etc.

For the same reason, stained sections of nerves, hardened in chromic acid solutions, or salts, usually fail to give a correct picture of the ratio between size of axis-cylinder and medulla, since the axis-cylinder shrinks up within the swollen medullary sheath, and forms in cross-section the well-known "sun-figures."

The osmic acid method gives better, though still not unexceptionable, results. The ratio between axial space and medulla was estimated by M. Joseph in the electrical nerves of *Torpedo* as 1 : 3–5. Within this great axial space the combined osmic acid and alcohol method gives, both in longitudinal and in transverse sections, a very delicate network ("axial reticulum" of Joseph), which Joseph assumed to be preformed, and the meshes of which should contain the axial fibrils, that do not appear in preparations treated by this method. Joseph further asserted that the "axial reticulum" is in direct connection with the neurokeratin network of the medullary sheath; but this, as Kölliker justly remarks, is rather evidence *against* preformation, since the existence of the latter as a preformed constituent of the medullary sheath is at least doubtful. The figures described by Joseph in many respects resemble the structural relations predicated by Bütschli of the axis-cylinder in its widest sense. The fibrillated structure here—as in muscle—consists of a longitudinal series of rods, the thicker lateral walls of which are united by very fine cross-bridges. With a medium power this gives the appearance of parallel longitudinal striation. It is uncertain whether this rod-structure of Bütschli is really preformed, or is merely the effect of reagents. In tissues of such excessive lability the last hypothesis is always possible. Moreover, there are certain

physiological indications in favour of isolated and separately conducting fibrils (which would be out of place in this chapter), rather than a conducting network.

The presence of varicose swellings along the single fibrils, or finer bundles of fibrils (slender axis-cylinders), must also under all circumstances be regarded as the effect of reagents. These swellings appear freely, and in fact uniformly, both with the gold method and with methylene blue, and are from the last fact regarded by many authors as pre-existent. And the regular appearance of varicosities in the end-plates of both motor and sensory nerves in still living organs (muscles able to twitch, etc.) is apparently in favour of this assumption. Nevertheless, Biedermann, along with many others, is of the opinion that varicosities, under any conditions whatever, are abnormal manifestations, due to commencing coagulation, or rigor—the first visible sign of dissolution.

One important fact that has hitherto been overlooked is the marked variation in calibre that occurs in both medullated and non-medullated, central and peripheral, nerve-fibres. This is, perhaps, most conspicuous in a large nerve-trunk stained with methylene blue, or in the ventral cord of crustacea and insects, but the difference is also striking in the medullated nerves of vertebrates. If, as we might expect, this is related with functional dissimilarity, the mere anatomical differences (apart from physiological reasons to be considered below) would be decidedly against the homogeneity of all nerve-fibres so often insisted on, according to which the differences of excitatory effect must be referred solely to differences in the terminal organs. As regards further histological details, it may be stated that large ganglion-cells usually give rise to thicker nerve-fibres than the small cells, and that all peripheral fibres become finer in proportion as they approach their (peripheral) end; this is seen more especially at all bifurcating-points of motor and still more of electrical nerves. Within the central system the contrary often occurs, and the nerve-fibre enlarges in diameter from the parent cell outwards.

CHAPTER VIII

CONDUCTIVITY AND EXCITABILITY OF NERVE

I. Phenomena in Nerve-Fibres

Conductivity is the chief and indeed exclusive function of the nerve-fibre, and the principal facts relating to it have next to be considered. There is absolutely no fundamental difference in the conducting of an excitatory process within any kind of excitable conductive protoplasm, *e.g.* muscle and nerve. In both cases *normal continuity of structure* seems to be an indispensable condition of conductivity, the excitation, at least in nerve-fibres, being directly transmitted from point to point. Recent conclusions as to the finer anatomy of the central system, on the other hand, render it highly probable that there is here an exception to the rule, inasmuch as the transmission of excitation, more especially from ganglion-cells to nerve-fibres, and *vice versa*, is effected not by continuity but by contact—contiguity—only.

It has already been pointed out in muscle that excitation under certain normal conditions remains localised to the directly excited fibre, and does not cross over into adjacent fibres. The same is true of nerve, whether medullated or non-medullated. Kühne (9) succeeded in exciting single fibres of the frog's sciatic by the unipolar method, upon which only the correlated muscle-fibres contract. The isolation and independence of the single fibres is confirmed by the effect of partially dividing a nerve-trunk; only a certain part of the tract supplied by the nerve will then be paralysed. When a nerve-fibre bifurcates, the excitation of the trunk is of course transmitted to all its branches. The ramifications are most abundantly developed within the central organs, but occur also in the peripheral terminations (muscles, electrical organs, etc.), and even, though more rarely, along

the nerve-trunk. As an instance of the first we need only recall the wealth of ramifications of the single processes of monopolar

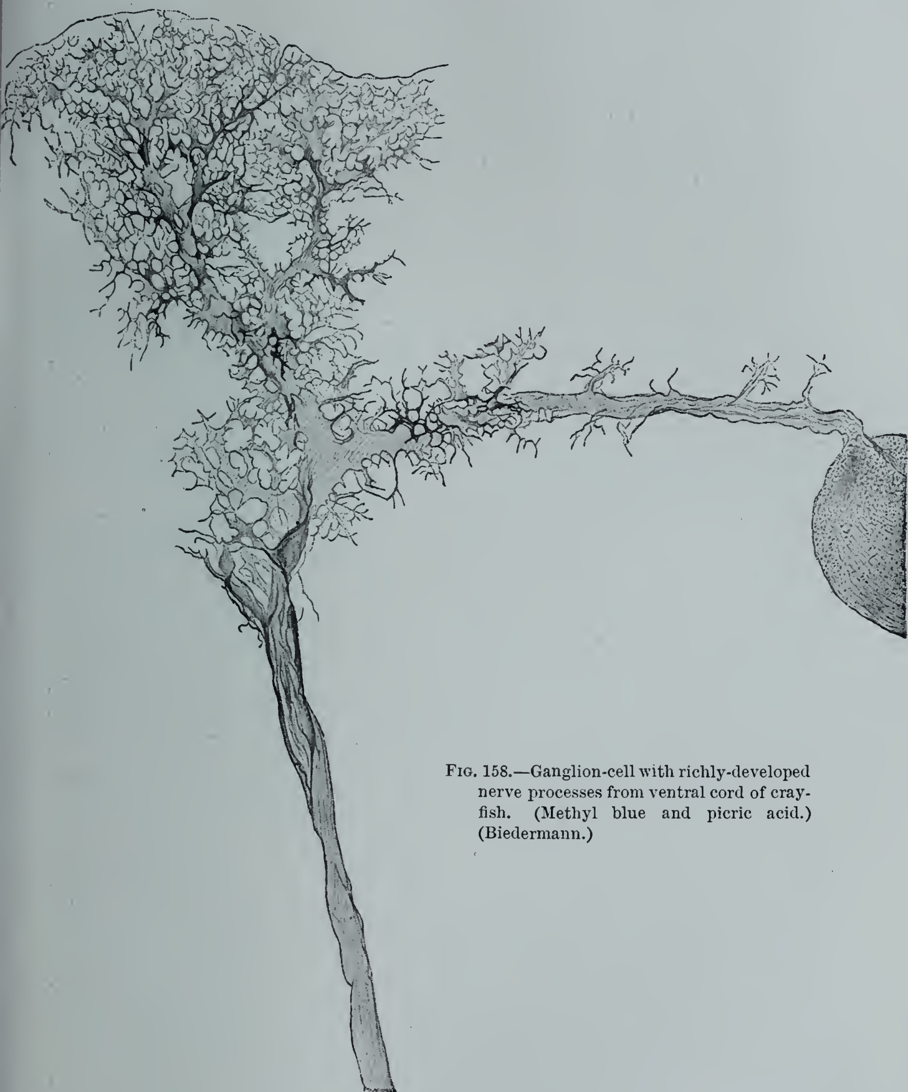

FIG. 158.—Ganglion-cell with richly-developed nerve processes from ventral cord of crayfish. (Methyl blue and picric acid.) (Biedermann.)

ganglion-cells in the ventral cord of crustaceans and worms (Fig. 158), as well as the "collaterals" from the vertebrate spinal cord. Here the branching obviously forms connection between various

more or less remote parts of the central nervous system. The ramification of (peripheral) nerve-fibres is, however, most striking in the electrical organs of certain fish (vide *Electrical Fishes*), which must in the majority of cases be regarded as transformed muscles. Thus in *Malapterurus* the whole of the paired organ, consisting of thousands of separate plates, is supplied by a single nerve-fibre, which must accordingly bifurcate an immense number of times in order to subserve each electrical plate, and the same is found in other electrical fishes. These are the cases which throw most light on the functional significance of the bifurcation of peripheral nerve-fibres. It is obvious that this must occur most freely in cases where no *isolated* activity of the end-organ is required, but where, on the contrary, the individual elements are affected as far as possible simultaneously, and for the same purpose. This also applies to muscles which subserve movements of a low degree of complexity, *e.g.* the rigidly-imprisoned muscles of crustacea and insects, where the nerves display a wealth of ramifications (Fig. 150).

The same relations exist, according to Stannius, in most motor nerves of fish, and in those to certain muscles of Amphibia (Fig. 159), where they are again explained by the low grade of co-ordinated movement in these animals. The higher the latter, the more a muscle is appointed, bundle by bundle, to engage in co-ordinated movements—the more local will be the distribution, and the less numerous must be the ramifications, of its motor nerve-fibres (Fig. 159).

As regards the mode of division in the non-medullated fibres of invertebrates, there is a great diversity, both in the central organs and in the periphery. Every kind of transition exists, from simple dichotomous branching to the richest arborisation. As two main types we may take the ramifications of the axis-cylinder processes from the central ganglion-cells in the ventral cord of worms and crustacea, and the muscular nerves of the latter. Both these types occur along the same axis-cylinder, the central and more or less richly branched portion being separated from the peripheral expansion by an undivided or but little branched part. Within the central organs the thick fibres give off numerous and very fine lateral branches, which again arboresce freely, so that the difference in calibre between stem and branches of the axis-cylinder is often considerable, while in the peripheral expan-

sions the type of strict dichotomous branching obtains. We could hardly find a better example of this than the abductor muscle of the crayfish claw with its nerves (3). Here the finer trunks invariably contain, within a stratified sheath of connective tissue, two axis-cylinders of very unequal diameter, and stain-

Fig. 159.—Nerve-cords from the costo-cutaneous muscle of a frog injected with methylene blue, showing numerous divisions and Ranvier's crosses. (Kölliker.)

ing differently with methylene blue. If these are followed down to the periphery, it will be found that both axis-cylinders divide at exactly the same point; this is repeated at each new bifurcation, even to the finest branches, so that the number of ramifications is conspicuously increased (Fig. 150). Both in the central organ and at the periphery, the ratio of magnitude between trunk and branches is remarkable. The dichotomous

division rarely occurs so that both branches are equal in diameter; one twig is usually much finer than the other, and there is frequently a marked disproportion, since a very thick axis-cylinder may give off an excessively fine lateral branch.

We shall have more to say later as regards the mode of division of vertebrate nerves, especially under the interesting relations which obtain in the electrical organ of the torpedo.

The law of isolated conduction does not apply within the central organs in the same sense as in the peripheral nerves and their terminations. Here the conditions for irradiation of excitation on all sides are obviously present, as appears more particularly from the manifestations of strychnin tetanus, where the stimulation of one or a few sensory nerve-fibres may, through the spinal cord, throw nearly all the striated skeletal muscles into active excitation. If, under normal conditions, the same localised stimulus calls out one co-ordinated (reflex) movement only, confined to one definite group of muscles, we may in a certain sense speak of isolated conduction. But the reason why the excitation in this case follows definite and invariably uniform paths, lies, not in a sharply-defined anatomical connection of the nervous structures involved (since these must on the contrary be connected on all sides, as regards conductivity, within the central organ), but in certain special conditions, excitatory or conducting, along certain "canalised" paths "or lines of discharge" in the gray matter.

Wherever an excitable substance is endowed with highly-developed conductivity, there is inevitably an equal irradiation of the excitatory process on all sides, so that it almost appears inevitable that each nerve-fibre, like a muscle-fibre, must conduct in both directions. At the same time, the fact that every nerve-fibre is naturally connected with an organ of excitation and a peripheral organ, renders it impossible that any direction of conductivity, other than from the former to the latter, should produce a recognisable effect. Many efforts have, however, been made to obtain a direct experimental proof of the matter. Such are more particularly the attempted union of the central end of sensory, and peripheral end of motor, nerve-fibres that have been divided.

Without going into the earlier and by no means unexceptionable experiments of Bidder, Philipeaux, Vulpian, and others, who endeavoured to unite the central stump of the sensory ramus lingualis trigemini with the peripheral end of the hypo-

glossal nerve, we may refer to the recent repetition by Kochs (10) of Paul Bert's experiment, in which the exposed tip of a rat's tail was grafted on to the skin of the back, and then cut off at its original attachment after the wound had healed up. After a short time sensibility is restored in the transplanted tail, apparently indicating that the not yet degenerated nerves were able to conduct excitation in a direction opposed to the normal. These experiments were, however, shown by Kochs to be quite inconclusive.

On the other hand (apart from certain observations of du Bois-Reymond on the transmission of the negative variation in both directions), we must reckon as genuine experimental evidence for the double conductivity of nerve, the experiments on branching nerve-fibres, undertaken by Kühne (11) in the intra-muscular nerve-branches of different frog's muscles, *e.g.* sartorius and gracilis; by Babuchin in the still more suitable organ of *Malapterurus*. The delicate nerve, which enters the middle of the sartorius by one side, divides within the muscle, so that the single fibres that constitute the bifurcations branch many times dichotomously.

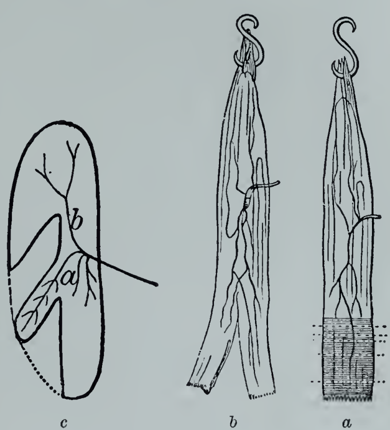

FIG. 160.

When Kühne threw the broad upper end of the muscle into heat-rigor by dipping it into warm oil (Fig. 160 *a*), the half which remained normal twitched on cutting the rigored portion with scissors, showing that excitable nerve-fibres could still be mechanically excited between the rigored and dead muscle-fibres, and thus carry the excitation *centripetally* into branches which divide above the rigored portion of the muscle. Still more convincing is the so-called "bifurcate experiment," in which the broad end of the sartorius is split up lengthways, when excitation of one fork nearly always produces an accompanying twitch in the other (Fig. 160 *b*). Since any propagation by secondary excitation from fibre to fibre seems to be excluded in normal muscles, the only possible interpretation is that one twig of the branched nerve which supplies both forks

is excited, and the excitation conducted in the first instance centripetally. Later on, Kühne attempted the same experiment successfully on other muscles, *e.g.* in the frog's gracilis. As is seen in Fig. 160 *c*, the entering nerve divides into two branches *a*, *b*, one of which is cut round so as to form a lobe; and on exciting this (by incision) the whole muscle invariably twitches. Since in this case also there are divisions of the fibres at the point where the entire nerve divides, the experiment is conclusive for centripetal conduction in the branch that supplies the lobe. We shall return later on to Babuchin's experiment; in this there is a discharge of the entire organ when any twig of the peripheral ramification of a single nerve-fibre is stimulated. As in Kühne's experiment, the excitation in the centrifugal nerves must at first travel centripetally, in order to spread to all the other branches (12).

If the axis-cylinder were homogeneous, the bifurcate experiment with sartorius, as well as the analogous experiments on other muscles and on the electrical organ of *Malapterurus*, would be clear and unimpeachable. On stimulating the lesser rami, the excitation would take a backward course to the point of division, and then presumably travel in the same centripetal direction along the fibres of the trunk, taking the normal centrifugal path only in the other peripheral ramifications. The axis-cylinder, however, is not homogeneous, but is composed of fibrils, and there is much to indicate that these are the true conducting elements. Hence we cannot regard any tract of the nerve as a physiological unity, but must recognise as many isolated paths of conduction as there are fibrils. Then, however, the results of the bifurcate experiment would, as Kühne points out, be conclusive for double conduction in the nerve under a succession of premises only. If the law is admitted, it implies at the dividing point of a primitive fibre a further division of axis-cylinder fibrils also (Kühne). When Max Schultze was elaborating Remak's theory of the fibrillar structure of the axis-cylinder he came to the opposite conclusion. He believed the nerve-fibres to contain from the outset all the fibrils destined for the peripheral expansions, so that in the branching of the axis-cylinder there would only be an unravelling, or bending aside, and no actual division of fibrils. On the other hand, there are many facts against this conclusion. Wherever nerve-division is present, the sum of the peripheral

sections of the fibres is in striking disproportion with the cross-section of the trunk. This is evident on comparing the inconsiderable axis-cylinder of the single fibre in the electrical nerves of *Malapterurus* with the area covered by the sections of its innumerable ramifications (Fritsch reckons the increase at 346,760 times): examination of any muscle that is rich in bifurcating nerve-fibres proves that the section of the trunk is far exceeded by the sum of the sections in the branches nearest to it. This is obviously not derived from increase of medullary sheath, and must be due to the axis-cylinders, so that two possibilities only remain in support of Schultze's hypothesis; the fibrils must either become thicker towards the periphery, or diminish in number at the cost of the stroma—neither of which can be demonstrated (Kühne).

The study of nervous excitation is much complicated by the fact that the excitatory process is not associated with any directly perceptible alterations within the nerve. We are everywhere thrown back upon the effects at its peripheral end, foremost among which, as a delicate indicator of the changes taking place in the nerve, is muscular contraction. Muscle—striated muscle in particular—is the surest index of nerve-excitation, and we owe nearly all our knowledge of the physiological properties of peripheral nerve-fibres to experiments on motor nerves. On stimulating any motor nerve there is a strikingly rapid reaction from the muscle (whatever the distance of the excited point), without any perceptible interval between moment of stimulation and commencement of contraction, no matter what point of the nerve is excited. This formerly led to very exaggerated statements of the rate at which these alterations in the nerve were conducted, and it was held to be incalculable.

Helmholtz (13) was the first who succeeded in measuring the rate of conductivity in nerve, by means (in the first instance) of Pouillet's method of time-measurement (Fig. 161), in which a battery current is closed at P by a switch when C is opened, at the moment of excitation, and broken again at B when the muscle begins to contract. During the short interval between P and B the current passes through the galvanometer G, and causes a perceptible deflection of the magnet proportional with the duration of closure. If two points of the nerve are stimulated, one remote from the muscle (a), the other as near it as possible (b),

the deflection in the former case will be greater. The difference gives the time in which the excitation travels from the distal (central) to the proximal (peripheral) point of excitation. At a later period Helmholtz arrived at the same result by a simpler method, *i.e.* the graphic record of the muscle twitches on stimulating two points of the nerve, as widely removed as possible. The difference in the latent period of the two curves, which are obviously non-coincident, but otherwise congruent (Fig. 162), corresponds to the rapidity with which the excitation is transmitted in the intermediate tract of nerve. In the motor nerves of the frog, at room temperature, this is about 27 m. per sec. Experiments on man by the same method (muscles of ball of thumb) give a much higher result (34 m.). Further observations of Chauveau on the nerves of smooth

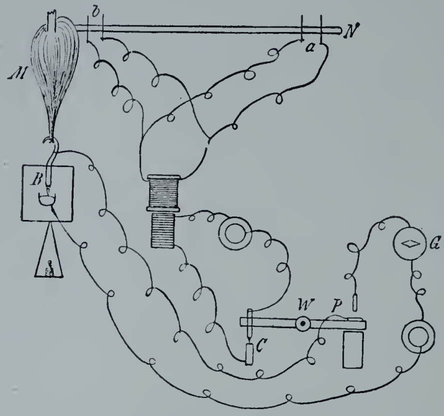

FIG. 161.—Rate of transmission of excitation in motor nerve of frog (Pouillet's method). (Helmholtz.)

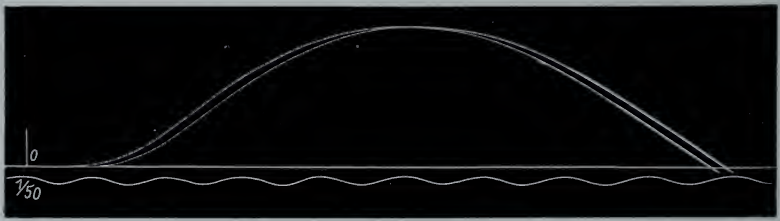

FIG. 162.—Separation of curves of twitch on exciting the frog's sciatic close to the spinal cord, and 5 mm. from the knee. (Engelmann.)

muscles in mammals are interesting, as showing that the rate of conductivity is much lower in these than in the nerves of striated muscle. It hardly reached 8 m. per sec. The rate of conductivity in non-medullated nerves of many invertebrates appears to be still lower, even when they are connected with striated muscles. Frédéricq and Vandervelde (15) found, according to the temperature (10°–20° C.), 6–12 m. in the claw-nerves of the

lobster, while Fick estimates the rate of transmission in the commissural nerves of *Anodonta* at 1 cm. per sec. only. Von Uexküll (16) has recently found values of 400 mm. to 1 m. in the nerves of the mantle of *Eledone.*

W. A. Boekelmann (17) has recently made some interesting attempts to estimate the rapidity of conduction in the non-medullated fibrils of the frog's cornea, by determining the interval at which a reflex movement (*retractio bulbi*) appears after mechanical or electrical excitation of the centre and periphery of the cornea respectively. The same ratio of values was obtained as for the medullated fibres of the trunk, a fact not without significance to the question whether the peristaltic movements of smooth muscular organs depend upon nervous conductivity, or upon direct propagation of the stimulus from cell to cell.

From all these calculations we arrive at the important conclusion that the excitatory process in nerve is transmitted at a comparatively low rate—incomparably less, at all events, than the velocity of light or electricity. If, as cannot be doubted, there is propagation of a material, chemical alteration of the substrate (substance of axis-cylinder), the qualitative constitution of the latter cannot fail to affect the process of conduction. And, in fact, the dependence of rate of conductivity upon different physiological conditions in the nerve is well known. Helmholtz, in his investigations on the motor nerves of frogs, observed a marked retardation of conductivity in the nerve, as the effect of cold. Frédéricq and Vandervelde again found that the rapidity of nervous conduction in the lobster depended, to a great extent, upon season and temperature. Nerve in this respect behaves analogously to muscle and all other excitable protoplasm. This correspondence is another proof that the process transmitted in the nerve is really a similar alteration to that in all excitable conducting plasma, *i.e.* a *chemical* process associated with metabolism. These observations are not unnecessary, in view of certain facts and hypotheses to be considered later.

Sustained pressure and compression of the nerve may seriously injure conductivity, and it is to be remarked that this seems to occur in a different degree in motor and in sensory fibres—Lüderitz (18) and some others finding the pressure-effect earlier in the former, Zederbaum (19) and others in the latter.

The action of *anæsthetics* upon the conductivity of nerve is

very remarkable, and of great theoretical interest. We found (vol. i. pp. 359, 450), in considering the effect of ether on muscle, that conductivity is first abolished, next contractility, and last of all local excitability. This last is still expressed in certain secondary electromotive phenomena (including the positive polarisation current), and in the demarcation current, at a time when contractility is already abolished. In nerve also, conductivity appears to suffer in first degree from the action of ether, chloroform, alcohol, etc., as appears directly from the persistence of the nerve-current with abolished conductivity (if this be accepted in the sense laid down above as the expression of persistent local excitation). By using a method first applied by Grünhagen (20), the conductivity of nerve may easily be abolished locally if the narcosis is confined to the lower end of an exposed frog's sciatic, by drawing the nerve through a glass tube which leaves the central end free, and is itself closed at both ends save for a small opening for the passage of the nerve. Three other glass tubes are fused into the wall of this tube; two serve to lead in the gases or vapours, the third is for the electrodes; the middle portion of the nerve rests upon the electrodes. There will then invariably be a stage of narcosis, in which the strongest excitation *above* the narcotised tract is ineffective, while a much weaker stimulus still excites *below* (*i.e.* in the tube). Eventually, of course, this part is also anæsthetised. If air is passed through the tube the normal condition will be reinstated. Under these circumstances, therefore, the conductivity of the nerve is extinguished, while local excitability is maintained, and even at first augmented, in the narcotised tract—a state which we found to be the rule in muscle under similar conditions (*supra*). In these experiments again, as pointed out by Pereles and Sachs (21), there are perceptible differences between the centripetal and centrifugal fibres of a mixed nerve (sciatic). If the minimal stimulus, which discharges a movement of the foot, is first determined above the central tract that is to be narcotised, along with the strength of stimulus necessary to produce a reflex movement of the leg from the web of the foot, the inevitable consequence of narcosis is the earlier disappearance of reflex than of direct movements. The same result follows even more infallibly from analogous experiments in which the nerve-trunk is excited by tetanising, now above and now below the etherised tract.

Here, too, the disturbance of the body caused by the centripetal conduction of a sensory excitation, on stimulating the lower point, is the first to die away, while movements of the foot can still be excited from above, although the stimulus which produces them is weaker than the other. "In local narcosis of the frog's sciatic, conductivity is first abolished in the sensory, and later in the motor nerve-fibres. On recovery from narcosis, the motor fibres sooner become capable of conducting than the sensory fibres."

More exact investigation shows that the ratio between conductivity and excitation in nerve may alter in quite another sense. Grünhagen (*l.c.*) observed, at a certain stage of CO_2 narcosis, that the local excitability of a (peripheral) tract of nerve may be considerably depressed, while the effect of stimulating the unpoisoned part of the nerve is unaltered, although the excitation process there discharged must be transmitted through the narcotised area. Similar experiments were carried out later by Szpilmann and Luchsinger, Hirschberg, Efron, Gad and Sawyer, Goldscheider, and lately in detail by Piotrowsky (22). From these the very significant fact appeared, that *with local application of alcohol vapour, ether, or chloroform, conductivity was as a rule first and most fundamentally affected at such parts of the nerve, before excitability underwent any perceptible diminution. With* CO_2, *on the contrary, as well as* CO, *conductivity is quite unaffected, while local excitability is quickly abolished.* These observations are the more striking because they seem to contradict the current opinion that excitability and conductivity are in the same ratio, *i.e.* that when one declines the other sinks, and *vice versa.* Yet we must admit the double capacity of nerve-fibres, on the one hand to conduct excitation, on the other to be thrown into excitation at any point of their course by external factors (stimuli), to be but different expressions of the same fundamental property of nerve-substance, and consequently inseparable. The most natural conclusion from this is, in the language of Hermann, that the excitatory process repeats itself constantly during conduction—that each particle of the nerve falls into the same state, whether it is affected by the impulse running along the nerve, or is directly excited by an external stimulus, so that the process of conductivity is first initiated in it.

From this point of view conductivity in nerve is, like every conductive process within an excitable substance, no more than

transmission of excitation from particle to particle, and might thus be designated as the propagation of the excitatory process.

On the other hand, there are several indications which make it probable that excitability (expectancy) and conductivity are distinct properties in nerve, and not in causal inter-relation. The first exact physiological observation of this was made by Munk (23), who noticed, in following out the changes in excitability associated with the dying of the nerve in a frog's nerve-muscle preparation, that the principal bifurcating points of the sciatic nerve could be insensitive to the strongest electrical stimuli, at a time when the muscle still responded by vigorous twitches to a much weaker excitation applied to more central parts of the nerve. A better known instance is that of Erb (24), who found that when, after crushing the sciatic nerve of frog or rabbit, regeneration had set in, and the lamed extremities were again moved normally by the animal, the part of the nerve that had been crushed, and was now regenerated, was still insensitive to electrical stimuli. Here, too, we must include the more complete experiments on the spinal cord (*infra*) by which Schiff was led to his doctrine of "æsthesodic" and "kinesodic" nerve-substance, capable, *i.e.*, of conducting, but not directly excitable. Above all, however, the experiments already quoted of Grünhagen, Efron, Gad-Sawyer, Goldscheider, and Piotrowsky, on the effect of local narcosis on motor nerve, have contributed to bring forward the view that the two processes of response to stimulus and conduction of stimulus are distinct from one another. Indeed, the fact that a peripheral tract of nerve under CO_2 narcosis is inexcitable, and yet transmits an excitation coming from a more central point, hardly admits of any other interpretation, save that excitability and conductivity may alter independently of each other.

If we are justified in regarding the process concomitant with the excitatory condition of a nerve element, as a stimulus by which the element longitudinally next to it is excited, conductivity must be a permeability of the nerve to certain influences which affect it in the longitudinal direction. We may, with Gad, denote this sensitiveness as "longitudinal lability." It is conceivable, and even probable, that the stimulus which one nerve-molecule exerts upon the next molecule may, although closely related to an external stimulus, or identical with it, find even more favourable conditions than the latter. This assumption (cf.

Hermann's *Handbuch*, ii. 1, p. 187) makes it possible that at a certain stage of localised narcosis local capacity of response may have sunk considerably, while conductivity, in consequence of the predominance of "longitudinal lability," is still intact (Grünhagen's CO_2 experiment). Under other conditions, on the contrary (as in treatment with alcohol), direct excitability declines much more slowly than conductivity, as normally occurs in muscle. In view of this fact, we shall hardly, with Szpilmann and Luchsinger, interpret the reaction as signifying that the excitation, starting from a distant normal point, has to pass through a longer and injured tract, losing thereby in intensity. But even Gad's view of a difference in the longitudinal and transverse excitability of nerve would appear to be fundamentally impossible, since the inexcitability of nerve to pure transverse passage of current is as well established for nerve as for muscle (Biedermann). A true grasp and right interpretation of these facts will only be possible when we know more about the manner in which one excited section of the nerve acts as a stimulus upon that section next to it. Innumerable examples show us that the excitatory condition *per se* does not necessarily imply conduction of the impulse to the contiguous sections. Localisation of persistent closing and opening contraction, the "positive anodic polarisation" (due to purely local alterations) of the narcotised muscle, the gradual introduction (*einschleichen*) of even strong currents into nerve and muscle, all prove sufficiently that the conditions of development, particularly as regards time, of the excitatory process are of fundamental importance to its propagation. It is conceivable that different substances might so affect the time-relations of the transmission of excitation from section to section, that the effects in question could be interpreted.

Helmholtz, in his experiments on the motor nerves of frogs, employed maximal stimuli, or else reduced the strength of stimulus at one point of excitation only so far that the twitches were equal in magnitude. The experiments which he undertook later with Baxt (14) on man, in which the muscles of the ball of the thumb were excited by stimulating the median nerve at two different places, appeared to show that the latent period on exciting the distal point of the nerve was regularly less with stronger excitation, while at the proximal point no effect from altered strength of excitation is perceptible. Hence we may conclude that strong excitation

is more rapidly transmitted in nerve than a weak stimulus. This view finds support in the later investigations of Valentin, Troitzsky, and Wundt, while Rosenthal and Lautenbach affirm that conductivity is independent of strength of excitation. From a recent and detailed research of v. Vintschgau (25), it appears that "when a frog's nerve is initially excited at two different points with that strength of stimulus (induction shocks) which causes the first, or approximately the first, maximal twitch, and the stimuli are subsequently increased from that point, there is a certain range within which the rate of transmission of the nervous excitation undergoes no essential alteration." So soon, however, as this has been exceeded, the rapidity with which the excitation is transmitted increases with the further augmentation of the stimulus, till it becomes impossible to measure it. A. Fick (26) found in the non-medullated commissural nerves of *Anodonta* that a strong stimulus was more rapidly transmitted in the nerve-fibre than a weaker excitation, and S. Fuchs (27) has recently arrived at the same result in determining the rate at which the negative variation is transmitted in the non-medullated nerves of the mantle of *Eledone*.

II. Phenomena in Fibres associated with Nerve-cells (Reflex Activity)

At this point it is desirable to discuss the question *whether the interpolation of ganglionic elements upon the course of the nerve-fibre has any, and if any, how much, effect upon the transmission of excitation.*

In stimulating motor fibres outside the central organ, this question has of course but little application; the most that can be ascertained is whether the transmission of excitation from nerve to muscle produces any perceptible delay in conduction or no. Certain experiments of Bernstein (*infra*) seem to indicate that such is the case.

Far greater importance attaches to the interpolation of ganglion-cells, in all excitatory experiments where parts of a central organ are excited directly, or by means of centripetal nerves. Exner (28) examined into the seemingly simple case in which the only question is whether the interpolation of a single ganglion-cell effects any marked alteration in rate of

conductivity. It is plain that if the time occupied by the passage of excitation through the ganglion is perceptibly longer than the known time of conductivity through an equal tract of normal nerve-fibre, there must be an interruption of some kind. The only histological elements in the ganglia which can present such an interruption are, however, the *nerve-cells.* The relations are far simpler here than in the central nervous system, where also the time occupied by the transmission of excitation has been taken as a proof of the existence of special elements interpolated along the course of the simple conducting paths; there, however, the delay in transmission must be referred not merely to nerve-cells, but also to the nervous network which is possibly present. Exner, who undertook to determine the time in which the centripetal wave of excitation traverses the frog's spinal ganglia, employed Bernstein's rheotome to measure (on the sciatic, ganglion, and posterior root) the interval between the excitation of the sciatic and the arrival of the negative variation in the fibres of the posterior root, as led off to the galvanometer. He obtained figures below those quoted by Bernstein for the rapidity in normal peripheral nerve, and concluded that conductivity was *not* blocked at the ganglion. The rheotome method is, however, open to many objections. Wundt (29) had previously tried to determine the point by testing the influence of the spinal ganglia upon reflex excitability. Curves of twitches from the muscles of one leg (in the frog), obtained by alternately exciting the opposite sciatic trunk and a posterior root on the central side of the ganglion (between the ganglion and the spinal cord), invariably gave a marked difference of latent period, corresponding with a delay in conductivity at the ganglion. Gad (30) repeated the same experiments on the jugular ganglion of the rabbit's vagus. The reaction to be determined was in this case the reflex modification of respiratory movements, by excitation of the vagus. The sole variable was the point, alternately central and peripheral to the ganglion, at which the stimulus was applied. The respiratory movements were graphically recorded by the usual method, and in order to ensure uniformity of external conditions at the centre during the respective tests, apnœa was induced, or the stimuli were carefully regulated for the same phase of respiration. The reaction-time yielded by these experiments was—

With excitation peripheral to the ganglion	0·123 sec.	(average of 148 experiments)
,, central ,,	0·087 sec.	(,, 97 ,,)
Difference . .	0·036	

V. Uexküll's recent experiments on the function of the stellate ganglion in *Eledone moschata* (16) bear on the same question. A large number of nerves (stellar nerves) radiate laterally from this ganglion, and supply the muscles of the skin and mantle. "On exciting the stellar nerves the near muscles first come into action, and then the more distant, in ratio with the conductivity of the nerves. With excitation above the ganglion the contraction of the near muscles is delayed, as is expressed in the gentler rise of the curve. The apex is, however, steeper, thus showing that the total effect on all the muscles is compressed into a shorter time. The *ganglion stellatum* would thus appear to correct the slower conductivity, since it enables the muscles of the mantle to perform more synchronic and therefore more effective movements."

If the *difference in reflex time*, on stimulating at different points, thus affords a gauge of the influence exerted by the ganglion-cells interpolated along the nerve-fibre, upon the time-relations of the excitatory process, the same is no less evident from the character of the reflex period itself. A reflex movement (*i.e.* a motor impulse in the muscular apparatus in consequence of a centripetal stimulus) can only occur when the centripetal path, which is first traversed by the stimulus, is connected with the efferent path by means of the central nervous system. The solitary ganglia of invertebrates, the spinal cord and bulb in vertebrates, are more especially the seat of these nervous processes. In 1855 Helmholtz first pointed out that the time between the impact of a stimulus and the corresponding reflex movement of a striated muscle was 10–12 times longer than the time required to conduct an impulse in a peripheral nerve of the same length. This assumes the rate of conductivity to be approximately equal in motor and in sensory nerves, as does in the above experiments appear to be the case.

The duration of an entire reflex process may be summed up in three factors: (1) the time occupied by conduction in a centripetal nerve, from the point of stimulation to the central end; (2) the time which elapses between the arrival of the excitation at the centre, and its transmission to the central end

of the centrifugal (motor) nerve; this is the "reflex time" proper (Exner's "reduced reflex period"); (3) the time required by the excitation to traverse the motor nerve and evoke a contraction in the muscle.

The rate of conductivity usually accepted for frog's nerve, *i.e.* 27 m. per sec., is by no means an invariable figure. Helmholtz indeed assumes that the excitation is transmitted at constant rapidity, but this is neither certain nor even probable. These figures must therefore stand for an upper limit of the reflex period, and in longer nerves than those employed there would presumably be a lower rate of transmission. Even with these reservations, however, Helmholtz's facts are incontestable. The excitatory process undergoes a considerable retardation during its passage through the spinal cord from sensory to motor fibres. *This delay must be attributed to the structure of the nerve-cells, in virtue of which they are distinct from their processes, the nerve-fibres.* The difference of constitution is best expressed by saying that the central nervous organ presents greater resistance to the transmission of excitation than the sensory or motor peripheral paths.

Like rapidity of conduction in peripheral nerve, only in a much higher degree, the reflex time, as the expression of the rate at which excitation is transmitted within the central organs, is conditioned by several factors, and is itself very variable.

The length of tract within the central organ, or, as it may perhaps be expressed, the number of ganglion-cells to be traversed, is of great importance. One fact must be mentioned by which central is distinguished from peripheral conductivity, and is rendered very complex. Each central organ consists of course of a multitude of nerve-cells, with centripetal and centrifugal fibres. If the law of isolated conduction obtained strictly within the centres also, so that each conducting path was isolated as in the peripheral nerves, each impulse from an afferent nerve-fibre could have but one definite localised effect, that would never vary under any circumstances. If, on the other hand, we recognise that the connection of different fibres by ganglion-cells (which finally establish a closer or more remote relation between all departments of the central organ) admits of conduction in all directions with equal facility, then impulses arriving at any part of the central organ would radiate diffusely without producing any definite and localised action. Neither the one nor

the other hypothesis, however, covers the case of reflex movements, the peculiarities of which are remarkable even in the lower vertebrates. The movements involved are always *co-ordinated*, *i.e.* they originate in the activity of a definite number of definitely grouped muscles. This is most obvious in reflex movements in the narrower sense, *i.e.* in those movements produced in striated skeletal muscle, after exciting a sensory nerve through a central organ.

If the end of a toe is pinched in a decapitated frog, the leg is withdrawn, and then remains quiescent. This is a typical reflex, *via* the spinal cord. The excitation, acting on the sensory nerves of the skin, travels centripetally from the periphery to the spinal cord, and gives rise to an impulse in the contrary direction—from cord to certain muscles of the leg. In this, and all similar cases, we must assume a *definite irradiation* of the excitation in the central organ, for the number of motor fibres excited is obviously in considerable excess of the number of primarily excited sensory fibres. Any touch, or least contact of the skin, with the fine point of a needle, suffices to throw a great number of muscles into simultaneous contraction, and as in the sensitive mimosa we concluded from the diffuse reaction consequent on local excitation, for the propagation of the stimulus along certain paths, so in this case we must assume that each sensory fibre is functionally connected with *many* motor fibres within the central organ—all possibility of transmission ceasing as soon as the latter is destroyed. *The law of isolated conduction, which is universally valid in the region of the peripheral nervous system, does not therefore hold good for reflex processes.* From the facts already discussed we may affirm that if it were possible to excite a single primitive fibre of a motor nerve, the muscle-fibres which are supplied by this fibre would alone contract, and the same is true of sensory nerve-fibres until they enter the central organ. In reflex movements it is otherwise; the excitation is here conveyed by one or a few sensory fibres *via* the central organ to a plurality of motor elements. It may be objected that a rigid anatomical relation between certain centripetal and certain centrifugal fibres still underlies this irradiation of excitation. This view is, however, unfounded. *The strength of the peripheral stimulus* is the most important factor in the diffusion of irradiation. In a headless frog, if the sensory

stimulus is strengthened, reflex movements occur in both legs, and subsequently in the arms and trunk. This implies diffusion of excitation over nearly the whole spinal cord, and almost all the motor nerves which originate in this part of the central organ are reflexly excited. The movements, however, are still co-ordinated throughout, *i.e.* the groups of simultaneously excited motor fibres are always in physiological correlation.

The transmission of excitation to remote muscles must obviously take a longer time under these conditions. If the reflex period is estimated for a muscle of the same, and for one of the opposite side (on stimulating a given point of the skin), the reflex time of the latter exceeds that of the former. The amount of this difference is *the time of cross-conduction.* There is apparently less resistance in the longitudinal direction of the spinal cord (Wundt, 29).

The specific characteristics of conductivity within the central nervous organs are least ambiguous in the striking changes which result from the action of certain poisons. It has long been known that in most vertebrates, after intoxication with *strychnin,* the slightest stimulation of any sensitive part evokes exaggerated uncoördinated muscular movements (spasms), which in warm-blooded animals soon end in death. Both earlier and later experiments concur to show that the spinal cord is an indispensable factor in strychnin-spasm, as in the initiation of reflex movements. Neither in peripheral motor nor in sensory nerves is excitability perceptibly modified by the poison. Strychnin must, therefore, be reckoned as a specific poison of the spinal medulla.

The introduction of minute doses (0·02–0·04 mgr.) at first produces no change in the frog, beyond a marked increase of reflex excitability. The reflex twitches appear with weaker stimuli, and with greater precision at each successive stimulus; neither in the duration of the latent period nor in the subsequent course of the twitch is there any perceptible divergence from ordinary reflex twitches. After somewhat larger doses (while, according to Rosenthal, the length of the latent period steadily decreases—Wundt states the contrary) the twitch changes gradually into a sustained tetanus, which appears with even the weakest stimuli, and is little increased with stronger excitation. At the climax of the strychnin effect, any stimulus capable of discharging the reflex at once produces maximal excitation. As

regards the dependence of a reflex twitch upon strength of excitation, it should be remarked that it is only within a very narrow range of stimuli that magnitude of contraction increases with that of stimulation. Directly the stimulus is capable of discharging any reflex it provokes a fairly strong twitch of the muscle, which cannot be much increased by further augmentation of stimulus: the reflex time, on the other hand, is diminished. According to Rosenthal (31), the reflex time may be so reduced with strong excitation that nothing remains of Helmholtz's phenomenon, and if the time which the excitation takes to travel from the point stimulated to the spinal cord, and thence to the muscle, is calculated, the sum of both will be approximately equal to the latent period as measured. The limited range within which increment of stimulus produces perceptible increase of reflex action diminishes with stronger doses of the poison, and finally vanishes (Rosenthal).

The phenomena exhibited by strychninised frogs are very characteristic. In normal reflexes the least stimulus applied to the hind foot induces flexion of the corresponding leg, while the extensor muscles remain quiescent. The action after strychnin poisoning is quite different; there is always pronounced contraction of *all* the muscles of the leg, and the extensors being the most powerful, the limb is stretched out convulsively. It is a question how the normal co-ordinated flexor reflex is converted after strychnin poisoning into the uncoördinated reflex of extension. If the normal dose is much reduced (= 0·0001 gr.) it will be found insufficient to transform the flexor into the extensor reflex, though there is still some effect on the spinal medulla, since a weaker stimulus provokes the reflex, and the reflexes appear more promptly and inevitably. As soon as these minute doses are exceeded, the spasmodic extension reflex sets in. While in the co-ordinated flexor reflex certain definite paths are alone excited, in the uncoördinated reflexes of extension *all* are excited simultaneously, and the extensors, as the more active, determine the movement of the limb. If the spinal cord is sufficiently strychninised there is a simultaneous contraction of all the skeletal muscles, discharged from every possible point of active sensory excitation—as though all the corresponding nerves were caught into a bundle and excited at the same moment. But if it is possible, under the action of strychnin, thus to excite all

the motor nerves from any sensory nerve of the skin, it is obvious that all the prolongations of the same within the reflex centre (spinal cord) must be similarly associated. Clearly the poison cannot alter the structure and direction of the central paths, along which the excitation travels in the spinal medulla. We must rather assume that the new relations into which the central nervous elements have reciprocally entered are due to a *chemical* alteration of their substance. The action of strychnin proves that the path taken by the excitation in the normal central organ is circumscribed, not by any definite arrangement of fibres, but by the mobility in a definite direction which characterises the mass through which the excitation is transmitted. If we picture the whole of the gray matter as a coherent network of homogeneous, excitable, and conducting plasma, in direct connection with the sensory and motor nerve-fibres (a conception that is not indeed borne out by recent histological discoveries), then the only possible explanation of the organised reflex movements which regularly follow on a given stimulus must be that there are certain "lines of discharge," along which excitation is normally transmitted, because there is here less resistance—the protoplasm is more excitable. The path along which a sensory excitation, calling out a definite reflex movement, travels in the spinal cord, has often been compared to a canalised track, and from a certain point of view the crude illustration suffices. But there is the further question of how this perfectly co-ordinated network of lines of discharge originated, and of whether it is possible during the life of the individual to form new combinations, and new excitatory paths to reflex movements. The question is too wide to be entered upon here; we can only say that there is some ground for assuming that every impulse traversing the central nervous system, along any path, leaves its traces behind it, inasmuch as it causes certain molecular alterations, which, as they become sharpened by repetition, facilitate the subsequent discharge of action along the same lines (Exner's "*Bahnung*"). This hypothesis not only accounts for the fact that *new* reflex combinations of movements may be formed during the life of the individual, but it also gives us the key to an understanding of those co-ordinated reflexes which the individual acquires as an "inheritance" from his ancestors.

If these facts show that the law of isolated conduction does

not hold in a strict sense within the central organ as in the peripheral nerves, the same is true of another great law, viz. that of "conductivity in both directions." The efferent (especially motor) and afferent nerves are known to enter the spinal cord of vertebrates by different roots. Central excitation of a divided anterior root never (even after strychnin poisoning) discharges any reflex movement or spasm. With regard to the structure of the cord we should, therefore, conclude that the protoplasmic processes of the cells of the anterior horn, in so far as they serve to transmit excitation, do so in one direction only. It would thus be characteristic of these cells that they confined the conductivity, which in ordinary nerve-fibres is in both directions, to one direction only (Gad). Recent conclusions as to the constitution of the gray matter, and more particularly the anatomical structure of the reflex arc, place the matter in another aspect. For if instead of continuity of substance we have merely *contact* between the end-branches of the conducting nerve-fibre ("terminal arborisations") and the "reflecting" (motor) cells of the ganglion, conduction in one direction becomes intelligible, and is no more surprising than the fact that excitation of a muscle does not simultaneously excite its motor nerve.

There is a striking dissimilarity in the action of strychnin upon different animals, pointing to corresponding and quite unknown differences in the chemical composition of the central nerve-cells. Among vertebrates, guinea-pigs and fowls are characterised by a special insensibility to strychnin (Leube, 32). And in most invertebrates the characteristic spasms are wanting, even with large doses of the poison. Claude Bernard first made the (often-confirmed) observation that the reflex excitability of invertebrates (crayfish, leech) is not altered by strychnin. Both in leech and crayfish the stages of excitation characteristic of vertebrates were entirely wanting, and he found only a rapid and primary (central) paralysis. Krukenberg (33) confirmed Bernard's conclusions, while Yung (34), on the contrary, witnessed sharp tetanic spasms in the crayfish which soon gave way to paralysis. Luchsinger (35), too, pointed out in invertebrates (leech, crayfish) that had been poisoned with strychnin, phenomena which he regarded as reflex spasms. In any case these only appear under certain conditions. Luchsinger, like Krukenberg, employed the ingenious method, first devised by C. Bernard for the frog, of

partial intoxication. A leech was divided into three parts by two ligatures; the ligatures stopped the circulation without crushing the ventral cord. Strychnin (0·0003 gm.) was then injected into the middle section, the effect, according to Luchsinger, depending wholly upon temperature. If the leech had been left for some time in water of about 8° C. it showed no sign of excitation, whereas the strychninised section of an animal that had previously been exposed to 25°–30° gave lively manifestations of excitation. "Waves of excitation ran from segment to segment, and if these quieted down, the least stimulus to the skin of the animal evoked disorganised movements." The unpoisoned ends throughout remained quiet. After a certain time the centre was paralysed. From this it would appear that there is no radical difference in the reaction of the spinal ganglia to strychnin in vertebrates and invertebrates, though gradations of sensibility are undeniable. The striking effect of temperature upon the action of strychnin, as exhibited in the leech, appears to some extent in the frog also, where it was first observed by Kühne, and subsequently worked out by Wundt.

Stronger doses of strychnin produce both in vertebrates, and even more rapidly in invertebrates, a condition similar to paralysis, the cause of which—as of the antecedent rise of excitability—is *central* in origin. The behaviour of the animal in this stage of strychninisation is highly suggestive of narcosis from anæsthetics (ether, chloroform, alcohol). We have already studied the peculiar effect produced by these reagents on all contractile substances, as also on *nerve-fibres*. The ganglion-cells must, however, be ranked first in order of sensibility, in all animals.

The depressing effect of *anæsthesia* upon the reflex movements of vertebrates has long been known, and it may reasonably be concluded that the ganglion-cells of the centres are first and most profoundly affected in their normal vital properties by the substances in question—as shown by the final and complete loss of excitability and conductivity. It was Claude Bernard who first pointed out that the action of anæsthetics is universal, and takes effect upon all excitable protoplasm. All experiments, however, show that the different tissues in an organism are affected in very different degrees. On submitting man, or any vertebrate, to the action of chloroform or ether, it is the sensitive protoplasm of the cells of the cerebral cortex that is pre-eminently

affected by the narcotic. Consciousness, conscious sensation, and voluntary movement—in short, all psychical activities in the narrower sense—are extinguished, while reflexes still continue. Reflex function is next abolished, nerve, muscle, glands, etc., remaining still unaltered. This explains why the vital functions survive, and why at its early stages narcosis is not directly dangerous to common vitality. The anæsthesia of the surgeon is really incomplete; it affects only the most susceptible elements of the central nervous system, while the other excitable parts (muscle, nerve, glands, etc.), although equally accessible to narcosis, are attacked later, long after the functions of the nervous centres have been abolished. Under all circumstances, however, *excitability and conductivity are indubitably functions of the protoplasm of the axis-cylinder in nerve-fibres also,* a conclusion that is significant in regard to certain theories to be discussed below.

III. Influence of Various Conditions upon Excitability of Nerve

If the effect of certain poisons thus leaves no doubt that *the central and conducting parts (cells and fibres) of the nervous system differ essentially in their physiological properties,* the same conclusion is no less obvious from the consideration of many other circumstances which influence the excitability and conductivity of the nervous centres. *Temperature* is of the first importance; its marked action on the functions of all living matter is well known. The fact that frogs exhibit differences of reflex excitability at different temperatures, preserving it generally longer at low temperature than at high, has long been familiar, but accurate observations on the point are wanting, which is the more to be regretted since the existing data are very contradictory. On the one hand, it is affirmed that warming of the spinal cord to 24°–27° C. increases reflex excitability—the more transiently in proportion as the temperature is higher; on the other hand, Tarchanow and Freusberg find that when the trunk is packed with ice, the reflexes discharged from the hind limbs are considerably augmented—a fact which, if true, recalls the effect of cooling on striated muscle (*supra*), as discovered by Gad and Heymans. The point, in any case, requires further investigation. In the ganglion-cells,

too, the dissimilatory and assimilatory processes may be affected in different degree by cooling.

However this may be, it is certain that within a given range (which is lower for cold-blooded and higher for warm-blooded animals), increase of temperature produces increase of reflex excitability. The next point is to determine this range experimentally. Excessive rise and fall of temperature are alike injurious to all excitable tissues. At high temperatures heat-rigor (paralysis) overtakes the protoplasm; excitability is of course affected at a somewhat lower limit. If a frog is kept for some time at a temperature of 30°–38° C., it falls into a state of apparent death. The heart still beats, but the animal gives no reaction—even the strongest stimuli have no perceptible effect, and localised muscular contractions are alone discharged. If the frog is then placed in cold water for a short time, it soon recovers all its central functions. Reflex movements of the throat-muscles appear first, then spontaneous respiratory movements, and finally the reflex excitability of the spinal cord is also restored. Later still the other centres of the medulla oblongata, and last of all the cerebrum, resume their activity, along with the power of voluntary movement. This sequence recalls the effects of *increasing venosity of the blood.* That the gases contained in the blood must be quantitatively and qualitatively normal, has long been recognised in warm-blooded animals as a necessary condition for the normal functioning of certain parts of the central nervous system, more especially the "respiratory centre," and if the gas exchanges of the blood are interrupted, *i.e.* if an animal is suffocated, a succession of striking excitatory effects arising in the central organs makes its appearance. These involve not merely the respiratory centre, vaso-motor centre, etc., but the whole of the central nervous system, which falls into a state of exaggerated excitation. The same occurs (in warm-blooded animals) when the blood-supply is entirely cut off. Blood—and blood of normal composition, more especially with regard to its contained gases—is absolutely indispensable to the preservation of the functions of the nervous centres; but it is indispensable in very different degrees to warm and cold-blooded animals. If we ligature the heart of a frog, or place the animal in a medium devoid of oxygen, it long retains the power of voluntary movement—leaps, swims, feels, etc. Interruption of the circulation does not at

once abolish the functions of the central nervous system. The entire blood-supply of a frog may even, as Cohnheim pointed out, be replaced by physiological salt solution, and the normal functions of the nerve-centres will none the less continue unchecked for hours at a moderate temperature. If the experiment is inordinately prolonged, the reflex functions are gradually extinguished. But even when the aorta has been obstructed for hours, or after prolonged exposure to a deoxygenated atmosphere, the frog will recover completely. The functions of the great nerve-centres are first attacked, and much later, the peripheral excitable parts (nerve and muscle). The different elementary constituents—tissue-elements—again are variously sensitive to the cutting-off of the blood-supply, and resulting changes in metabolism. Some die quickly, as the gray matter of brain and cord; others more slowly, as the peripheral nerve-trunks and muscles. In warm-blooded animals the phenomena are essentially the same, but they occur much more rapidly; here, too, the central system is first to die, and then the peripheral nerves and muscles. This is true, both of anæmia, and of the asphyxia due to poverty of oxygen in the blood. Stenson's experiment is a good illustration of the first of these. If the abdominal aorta is ligatured in a warm-blooded animal, paralysis of the hind limbs occurs in a few minutes, although excitability and conductivity of nerve-trunks and muscles remain perfectly normal.

The dependence of the central nerve-cells upon the blood is indicated in the anatomical distribution of vessels within the white and gray matter of the central organs, as well as by the vascular poverty of the peripheral nerves. It is known, moreover, that a protracted interruption of the blood-supply induces more or less definite histological changes in the ganglion-cells of the gray matter of the spinal cord in warm-blooded animals: these may even disappear altogether (degenerate), while the fibres of the white matter are still intact (36).

The facts thus briefly summed up show that the organ of reflexes, the automatic central structure of the brain and spinal cord, differs in a marked degree (and that by a whole series of characteristic peculiarities in excitability and conductivity), if not fundamentally, from other excitable parts of the nervous system. The central nerve-cells are peculiarly susceptible to certain poisons. Strychnin specifically affects the excitability of the ganglion-cells

of the spinal cord, while it has little appreciable action on nerve and muscle; anæsthesia notably attacks the central structures first, and the heart, peripheral nerves, and muscles at a later period only. The same facts are met with when the temperature is raised above a certain limit. Finally (and this is perhaps the most characteristic), the amount of gas contained in the blood is of the utmost importance to the excitability of the nervous centres, which, more especially in warm-blooded animals, are so extraordinarily sensitive to changes in their normal metabolism (whether from anæmia or from dyspnœic condition of the blood) that they can, in this respect, hardly be compared with the peripheral nerves and muscles.

Accepting the highly probable assumption that the central and peripheral nerve-fibres are, in the main, alike in physiological properties, as also in structure and origin, it is easy to understand why the motor consequences of direct excitation of the central organs, and more especially of the spinal cord, should differ in many respects from those of direct excitation of the peripheral motor nerves, and should appear to depend essentially upon the same conditions as reflexly-provoked movements. This is the immediate outcome of the fact that each motor nerve-fibre (of the anterior root) is the process of a nerve-cell, and that the spinal cord can only affect it indirectly through the cell. Disregard of this fact can alone account for the acceptance of the singular theory that the central nerve-fibres conduct, but are not excitable.

The contrast is the more striking, since, on the one hand, the central nervous organs, brain and spinal cord, seem to react in such an extraordinary degree to the weakest natural "organic" stimuli, and to propagate the excitation, while, on the other, the nerve-fibres which participate in the structure of the nervous centres are scarcely to be distinguished anatomically from those in the peripheral nerves.

On reviewing the experiments in point, we find that they all aim at establishing that movements consequent on excitation of the central organ are not reflexes, and ascertaining safe objective criteria of sensibility in the animal. Thus Van Deen tried to exclude the objection just made (*re* interpretation of motor effects of excitation from the spinal cord) by a special method which has since been frequently repeated. He exposed

the spinal cord of the frog from about the 3rd to the 5th vertebræ, divided the roots of all the spinal nerves except those of the sciatic, and pushed in a small knife horizontally above the lumbar swelling, so that it divided the dorsal and ventral halves of the cord. If the knife were then drawn forward in the same position to the upper boundary of the cord, there would be a free lobe, composed of the posterior columns, a greater or less proportion of the lateral columns, and gray matter; which, after dividing its anterior and posterior ends, could be removed altogether. In this way the whole posterior (dorsal) half of the spinal cord, along with the entering sensory roots, was eliminated, and the possibility of discharging reflex movements at the seat of excitation excluded. If the isolated ventral part of the cord was then mechanically excited, Van Deen sometimes obtained movements of the hind-foot, which he at first believed to be due to direct excitation of the anterior column. Meantime Stilling drew attention to the possibility that the highly sensitive anterior roots of the sciatic plexus might be excited in these experiments by slight traction of the cord, and Van Deen himself, before the publication of Stilling's work, had been led by new experiments to the remarkable conclusion that neither the anterior column nor the other parts of the spinal cord were excitable—thus first formulating a dogma destined to prevail in physiology for many a decade.

In subsequent demonstrations Van Deen did not even consider it necessary to remove the upper dorsal half of the spinal cord, but employed the uninjured medulla which protruded from the vertebral canal. Mechanical, chemical, or electrical excitation of the cephalic end failed, it was said, even with strong currents, to produce any symptoms of activity in the muscles of the posterior extremities.

Schiff (37) meantime, without knowing of Van Deen's earlier publications, arrived at the same conclusions, as the result of a series of experiments on the spinal cord of different warm-blooded animals. Total insensibility of the paths which conduct painful influences ("æsthesodic"), and inexcitability of the paths along which motor impulses travel ("kinesodic"), seem here, too, to be the general rule. Schiff's experiments were in the main analogous to the first of Van Deen's, since he removed the posterior columns in the partially exposed cord for a distance

of 5–6 cm., when the careful application of electrical, as well as chemical, or mechanical stimuli (pricking, squeezing with forceps) to the segment of cord under observation failed to produce any muscular movement, or sign of painful sensation.

The conclusion drawn by Schiff from this experiment, to the effect that "in such an animal the (painful) sensations *conducted* through the spinal cord which has been deprived of its posterior columns cannot be *excited* by artificial stimulation of the cord itself, and that motor excitability is also wanting in the latter, although it is fully able to *transmit* a motor impulse," was under these conditions very natural. It proved, however, impossible to excite the entire uninjured spinal cord of a warm-blooded animal without effect, even after the most careful removal of the posterior roots, since (according to Schiff's view) the irradiating fibres of the sensory roots "still invest the posterior column with a marked degree of sensibility, which is transmitted farther, and results partly in painful sensations, partly in reflexes of various kinds, at different levels of the spinal medulla." Schiff, moreover, differs from Van Deen in ascribing excitability to the nerve-fibres which run centripetally along the posterior columns. Excitation of these never produces pain, but causes exclusively tactile sensations, or "kindred sensations of less intensity," betrayed chiefly by alterations in the size of the pupil on electrical or mechanical stimulation of the mostly isolated posterior columns.

Without entering into details of the numerous attempts to decide the *pros* and *cons* of the Van Deen-Schiff theory, we may state that on the one hand Fick (37), followed by Luchsinger, brought forward experiments which determined the existence of directly excitable motor elements in the anterior (ventral) section of the frog's spinal cord, while on the other a series of communications from Ludwig's laboratory asserted the excitability of centripetal fibres running in the lateral columns. It is known that the excitation of sensory nerves frequently produces a considerable rise of blood-pressure, owing to increased resistance in the arteries from the reflex constriction of numerous vessels. Dittmar (37) showed that both electrical and weak mechanical excitation of the central end of the rabbit's spinal cord, that has been deprived of its posterior columns for some considerable distance, produces the same marked rise of

blood-pressure. From this he inferred the direct excitability of the "æsthesodic" elements of the cord, which, according to Miescher's experiments, are situated chiefly in the lateral columns.

Schiff disputes the validity of this experiment, and more particularly denies that the centripetal fibres of the lateral columns, from which the reflex is discharged, can be termed "sensory" in the true meaning of the word. This, however, is a by-point in the present connection, where the main object is the determination of direct excitability. How far Schiff's later objections (in which he refers the results of Dittmar's experiments entirely to spread of current to the posterior columns, that are alone excitable) can be justified, must provisionally be left undecided.

The direct excitability of the *motor* elements of the spinal cord has, on the other hand, been firmly established. Fick's early experiments above referred to, which were essentially founded on the first of Van Deen's, are open to the objection that the movements of the posterior limbs that appear when the ventral half of the frog's spinal cord deprived of its posterior columns is electrically excited, may be due to reflex or direct excitation of the fibres of the motor root — since there might be spread of current to the uninjured inferior portion of the spinal medulla. Nor is this objection completely removed by the fact that on dividing the ventral half of the cord immediately above the lumbar swelling, and laying the edges together again as closely as possible, the excitatory effect in question fails to make its appearance. On the other hand, the experiment of Van Deen and Fick is fully convincing, under the presumption that motor fibres run longitudinally in the ventral portion of the spinal medulla, and that their physiological properties coincide in all essential points with those of the peripheral nerve-fibres. And since there is no doubt (*infra*) that the excitability of peripheral nerves is considerably greater in the immediate proximity of a fresh section than along the continuity of the nerve, it is to be expected, if the motor fibres of the cord give a similar reaction, that electrical excitation will take effect at the cut end of the isolated ventral half of the cord sooner, *i.e.* with less intensity of current, than at a lower point, where — seeing the closer proximity of the roots of the sciatic — the danger of direct excitation by current diffusion is proportionately greater. Biedermann (37) found, as regards excitability to tetanising in-

duction currents, that the divided anterior columns of the frog's spinal cord gave—apart from quantitative differences—a reaction precisely similar to that of any peripheral motor nerve. If, with descending direction of the "break" shock, the electrodes connected with the secondary coil are (at not too great a distance) so placed that one is at first actually applied to the section, and are then moved farther and farther away, the initially marked effect of excitation diminishes rapidly, and soon disappears altogether. The first effect of stimulating with currents which, if directly applied to the free surface of the muscle, produce no visible excitation, and which are not felt by the tongue, invariably consists in a more or less pronounced tetanic disturbance of the muscles of the two posterior extremities, often amounting to regular tetanus. Stronger excitation often evokes co-ordinated movements. When the just effective stimulus at the transverse section of the anterior column has been determined, the electrodes (with descending direction of break shock, which alone acts at first) can usually be shifted into the immediate proximity of the lumbar enlargement—thereby greatly increasing the danger of direct or reflex excitation of the anterior roots—without producing any trace of excitatory phenomena in the muscles of the hind limbs. This, however, is only the case if the electrodes are shifted along the ventral surface of the anterior column. If they are applied to the inner surface, *i.e.* the cut section of the ventral half of the medulla, in direct contact with the exposed gray matter, there is never a perceptible difference of excitability at points near the cross-section, as compared with the deeper parts. It is doubtful whether this experiment by itself justifies the conclusion that in the last case the gray matter is directly excited, while in the former there is certainly excitation of the longitudinal nerve-fibres (in the anterior columns).

By using proper precautions we can thus excite the spinal cord of the frog (divided below the medulla oblongata, but not otherwise injured), without fear of complication by reflexes. It is sufficient to shift the exciting electrodes along the ventral surface of the cord, after determining that distance of coil at which the descending break shock takes effect in the immediate proximity of an artificial cross-section, at any point. The excitation of any other point along the cord, even close to the

lumbar swelling, is then absolutely ineffective. If these experiments establish the presence of directly excitable motor elements in the ventral half of the frog's spinal cord, it is on the other hand undeniable that there are important differences as regards both excitatory conditions and the nature and mode of the reaction, according as the muscle is stimulated by excitation of its motor nerve, or through the spinal cord. The comparative inefficacy of mechanical and of single electrical stimuli, as well as the total failure of chemical excitation, must be remembered. Nor is this surprising, since the motor fibres of the cord are not, like the peripheral motor nerves, in *direct* connection with the muscle, but are interrrupted by ganglion-cells (as proved, more especially by the observations of Birge, for the frog). This view is supported by the far-reaching analogies which exist with regard not merely to time-relations, and distribution, in direct (*i.e.* with excitation of the motor elements of the cord) and in reflex muscular movements, but also to the conditions of discharge in the two cases.

With reference, first, to time-relations, we have already seen that the transmission of the excitatory process from sensory to motor fibres, *via* nerve-cells, takes up a considerably longer period than the simple conduction of excitation through a corresponding length of nerve. Mendelssohn (37) has recently found that the reaction-time of the ventral half of the frog's spinal cord, *i.e.* the interval between the moment of excitation and the appearance of the gastrocnemius twitch on one side, is shorter than the reaction-time of the dorsal half. In other words, excitation of the ventral half of the spinal cord produces movement of the limbs more rapidly than when the same stimulus is sent into the corresponding point of the dorsal segment. The difference, according to Mendelssohn, amounts to 0·01–0·025 sec. This reaction indicates that (in accordance with theoretical presumptions) the muscular contraction due to direct excitation of the anterior column makes its appearance earlier than the reflex contraction discharged from the posterior column, the cause of the delay in the last case being the larger mass of interpolated gray matter.

The most significant factor in judging of the differences that result from stimulation of the spinal cord, and direct excitation of the peripheral motor nerves, is the fundamental difference in the physiological properties of nerve-cells and nerve-fibres, the former

being much more sensitive to changes in their normal metabolism, as well as to any kind of injury, than the latter. This is, however, most conspicuous on comparing the excitability of different parts of a motor organ (consisting of nerve-cells and fibres, along with their peripheral terminations in the muscle), solely with reference to the excitatory effects which each exhibits. It must obviously depend upon the momentary state of excitability, or conductivity, of the cellular elements interposed along the fibres, whether an excitation on the distal side of the same will produce any excitatory movement or no. And in fact we see that the reflex functions of the spinal cord may suffer, or be entirely abolished, under certain conditions, while excitability and conductivity in the motor and sensory portions of the reflex arc are not perceptibly affected. Luchsinger applied this unequal capacity of resistance in central nerve-cells and fibres to prove the *direct* excitability of the cord after local destruction of the reflex functions. Various cold-blooded animals with a long spinal column (snakes, blind-worms, tritons, etc.) were decapitated, the fore-part of the body being then plunged into salt water heated to 40°–45°, while the rest of the body was kept at normal temperature. The warmth soon destroyed the reflex properties of the cervical and dorsal medulla, while excitability and conductivity were still presumably intact in the long medullated fibres. If (as usually occurs) electrical excitation of that part of the medulla which no longer discharges reflexes can cause movements of the tail, these can only (according to Luchsinger) be due to direct excitation of the longitudinal motor fibres of the spinal cord. Schiff objected that the testing of reflex capacity in this part of the body by stimuli applied to the skin is no sure guarantee of the total destruction of the reflex functions of the spinal medulla. He pointed out the possibility of "intra-medullary" reflexes, which only fail to appear within the warmed segment, because its muscles are rigored by the previous exposure to heat. Schiff adduces experiments on bombinators and toads, in which, after warming the entire cord exclusive of the peripheral end of the *cauda equina* till the trunk-muscles were completely rigored, the reflex excitability of the hind limbs still persisted.

Nevertheless the low resistance in the gray matter of the cord, as compared with that of the white mass of the fibres, is indisputable. By this, *inter alia*, we may explain the fact that

the motor effect of direct excitation of the spinal cord appears the more plainly in the muscles of the posterior extremities, in proportion as the reflex excitability of the preparation is greater, while it fails altogether when the latter is extinguished. According to Birge's experiments (*supra*), the same elements of the gray matter of the lumbar cord (nerve-cells of the anterior horns) must convey the excitation in the one case from centripetal, in the other from centrifugal fibres, to the same fibres of the anterior root. The reflex centre of the posterior extremities would therefore not merely be thrown into excitation from periphery to afferent nerve-path, but also, as it were, possess two poles, one central (the motor paths in the cord), the other peripheral (the sensory fibres). All injuries that involve central conductivity are equally prejudicial to the effects of reflex and of direct excitation of the spinal cord.

The extraordinary sensitiveness of the central nerve-cells of warm-blooded animals to all disturbance of normal nutrition indicates *a priori* (as is confirmed by Stenson's experiment) that conductivity in the spinal cord will diminish and be abolished much more rapidly in all paths interrupted by ganglion-cells, under certain influences (especially anæmia or asphyxia), than it is in cold-blooded animals, so that experiments on the direct excitation of the cord involve much greater difficulties, and fail much more easily, than in the latter. Moreover, it is clear that the rapid and total interruption of the blood-supply to the spinal cord (taking precaution to avoid the cerebral circulation, and with artificial respiration), affords a working method of ascertaining the *uninterrupted* conducting paths in the medulla after exclusion of the others. For conducting paths which are blocked in a few minutes by anæmia cannot be regarded as the *direct* continuation of peripheral nerve-fibres. It is far less probable that a medullated fibre of the white columns of the cord should react differently to anæmia from the like fibre of a peripheral nerve, than that the functional disturbances that are induced by anæmia so much earlier in the cord than in the peripheral nerves should be located in the interpolated cells of the gray matter. And S. Mayer's experiments on the effect of anæmia produced on the rabbit's spinal cord by ligaturing the aorta high up, do in fact show that vaso-motor fibres originate in the medulla oblongata, and

traverse the spinal cord without interruption from ganglionic elements.

These facts respecting conductivity of excitation within the nervous centres suggest important conclusions as to the anatomical arrangement and reciprocal relations of the conducting paths. Starting with the fact that every nerve-fibre is connected inside or outside the central organ with at least one ganglion-cell (its parent-cell), it may be assumed that every reflex arc is built up of nerve-cells, and that these (especially the motor cells) are under the most favourable conditions for mutual conduction.

Histological investigation has so far contributed very inadequate support to this physiological postulate. It was indeed natural to regard the great multipolar ganglion-cells of the anterior horn, along with their numerous ramified "protoplasmic processes," and Deiter's axis-cylinder process passing directly into an anterior root-fibre, as the elements through which the functionally distinct nerve-fibres from the periphery are anatomically related at the centre. This view is expressed in Gerlach's theory, which represents the protoplasmic processes of the ganglion-cells as forming a rich network of the finest nerve-fibrils, connecting the cells of the anterior horn not merely with one another, but also with the posterior root-fibres, which also, according to Gerlach, terminate in a fine fibrous network after their entrance into the gray matter. Recent researches into the finer structure of the nervous centres (Golgi, Ramón y Cajal, Kölliker, Retzius, and others) have substantially modified the earlier doctrine of Gerlach in certain important physiological particulars. There is no proof of a central nervous network, as the anatomical substrate of irradiation of excitation. The cell-processes (nerve-fibres) which arboresce within the gray matter seem all to terminate freely, without anastomosing with the processes of other nerve-cells. Certainly it can only be said at present that no anastomosis has yet been detected; its non-existence may be questioned, in view of the wealth of ramifications exhibited by the protoplasmic processes. Golgi indeed denied the "nervous" nature of these processes, but his opinion must be disallowed, since in many cases all the processes are of the same character, and the nerve-fibre may even (as in the giant electrical ganglion-cells of *Malapterurus*) spring, not from the body of the

cell, but from the protoplasmic processes that interlace in a close network.

The physiological connection of the central motor elements is still, therefore, an open question, while the nature of their relations with the afferent (sensory) fibres may be regarded as histologically established.

The posterior root-fibres, which must be regarded as processes from the cells of the spinal ganglia, bifurcate (according to Ramón y Cajal and Kölliker), as they enter the cord, into two branches, running respectively upwards and downwards in the mass of the posterior column. These longitudinal fibres give off ("collateral") branches—mostly at a right angle—which enter the gray matter, and terminate in free dendritic ramifications (Kölliker's "arborisations"). The similarity of these bouquets to the terminal expansion of the axis-cylinder in the striated muscles of vertebrates at once suggests a similar relation with the motor cells of the spinal cord. Kölliker, indeed, maintains that the twigs of an arborisation (which usually carry a small swelling) are closely interlaced with the ganglion-cells, but never really anastomose with these or their processes. Contiguity is, however, indispensable to transmission of excitation. "Radiation" (*Anstrahlung*) from a free nerve-ending to another that merely lies near it (as in the olfactory glomeruli), or to a cell (as in the simple reflex arc), is an assumption the less justifiable since there is no sufficient histological evidence for a hypothesis so divergent from all prevailing views on conductivity of excitation.

Since each nerve-fibre represents the process of a cell, and forms with the same a physiological unit (neuron, neurodendron), it is intelligible that a nerve-fibre separated from its parent-cell should sooner or later undergo degeneration. Each nerve-cell is thus the "trophic" centre of the outgoing nerve-fibre, and the normal connection between them is one of the most essential conditions of the permanent preservation of conductivity and excitability in the nerve-fibre. In view of the facts above cited, we can hardly doubt that this trophic influence is largely due to the action of the *nucleus*, as follows, indeed, by analogy with other cells.

Seeing the extraordinary instability of the central ganglion-cells, the resistance which in peripheral *medullated* nerve-fibres preserves the fundamental vital properties (provided the nerves are

protected from drying, and other injurious circumstances) is very striking, and emphasises the radical physiological differences between the two. Excitability and conductivity will, in a nerve-trunk which is isolated for a considerable length, and connected only at one end with its terminal organ (in which the circulation is wholly abolished), persist for hours, even in warm-blooded animals.

Non-medullated nerves, on the other hand, are far more perishable. The nerves of crayfish and lobster, at least, do not maintain their excitability for even approximately so long a time as frog's nerves, when isolated and stimulated. Piotrowsky found the experiment quite impossible in summer, while excitability disappeared in winter after 8–10 min. Kühne also found the non-medullated olfactory nerve of the pike to be excitable for a very short time only.

It is evident that we can estimate the true duration of survival in an excised nerve only when the nerve alone, and not the terminal organ (which is the sole indicator of activity in the former), is withdrawn from normal conditions of nutrition. No certain conclusion as to survival in an excised warm or cold-blooded nerve can therefore, as a rule, be formulated from observations on a perfectly isolated nerve-muscle preparation: the muscle obviously becomes inexcitable long before the nerve.

The fact that nerves, when removed from their natural situation and laid across the electrodes, remain excitable for hours even in warm-blooded animals, points to an enormous power of resistance, and it follows that the medullary sheath is an effective means of protection.

If any excitation, best an exactly measurable electrical stimulus, be employed to test the excitability of a nerve which has been separated from its centre, by observing the gradual alterations in the reaction of the terminal organ (*e.g.* muscle), the alterations of excitability at any one point of the nerve, as well as at different points along its course, will be of a very involved character. The simplest hypothesis, as regards the former, is that the excitability of every particle of the nerve sinks in time by regular gradations to zero. Certain observations of Rosenthal (38) appear to contradict this theory, as showing that a considerable *increase of excitability* precedes its diminution, at every point. Biedermann, however, like Mommsen and more recently Werigo

(39), was not convinced of the accuracy of this last statement, and invariably found (if desiccation and all injurious influences were as far as possible excluded) a slow and regular fall of excitability at any point of the nerve, so far as could be determined on an excised frog's nerve-muscle preparation by comparing the heights of twitch, on stimulating with single submaximal induction shocks of uniform strength. Another fact, on the contrary, is easily confirmed. Valli, Pfaff, and Ritter observed that any (motor) nerve, after the death of the animal, or simply after separation from the central organ, invariably lost its capacity to produce twitches in the correlated muscle, on stimulation, first in its central parts, next in the branches, last of all in the ramifications by which it terminates in the muscle. This centrifugal march of death in the nerve (Valli and Ritter) might be expected at a very different rate in different animals, *i.e.* it is quickest in warm-blooded, slowest in cold-blooded creatures, the nerves of the latter retaining their excitability for days when protected from evaporation at low temperature. The interpretation of these observations is less simple than might be concluded at first sight. Du Bois-Reymond pointed out the possibility that the dying nerve might not be able to transmit excitation over as extended tracts as the normal living nerve, and Mommsen (*l.c.*), as well as Szpilmann and Luchsinger (22), afterwards subscribed to the same opinion. And, in fact, all phenomena corresponding with the Ritter-Valli law may be interpreted without difficulty under the presumption of an equal fall of excitability at all points, assuming only that conductivity sinks more quickly than the power of direct response.

At a further stage of dissolution, visible anatomical changes, known as fatty degeneration, occur in the nerve (more especially when medullated) that has been separated from its centre. If a mixed nerve is divided at any point, and the peripheral trunk examined after some days or weeks, the fibres will throughout be found uniformly altered, and the medullary sheath broken up or wholly disintegrated. The remains of the sheath will be visible as spindle-shaped lumps upon the fibre, in which, along with flakes of medulla, there are drops of fat of different sizes. Eventually, the connective tissue alone remains, all nervous structures having vanished. If the alterations in the central end of the divided

nerve are simultaneously investigated, they will be found only in the immediate neighbourhood of the cut surface, and are but little developed; further on, the fibres show hardly any perceptible changes, and the nerve also remains permanently excitable.

Waller's investigation of the roots of the spinal nerves threw much light on the subject, showing plainly that the ganglion-cells exert a "trophic" influence on the nerve-fibres connected with them, as indeed does every nucleated cell upon its non-nucleated prolongations. Degeneration of the peripheral end invariably follows the division of the anterior root of a spinal nerve, while the central end, which is still connected with the cord, remains normal. After dividing a posterior root the consequences vary according as the section is between spinal cord and ganglion, or is peripheral to the latter. In the first case the central end, which is connected with the cord, degenerates, and the degenerated fibres may be followed a long way into the cord itself (in the posterior columns); the end connected with the ganglion, on the contrary, like the ganglion itself, is unaltered.

After dividing the nerve on the peripheral side of the ganglion, the end connected with the latter is not affected, while the peripheral end degenerates. From repeated experiments, therefore, we must conclude that the cells of the spinal ganglion are the parent-cells (or trophic centres) of the posterior root-fibres, while the cord, and its large multipolar cells in the anterior horn, are the trophic centres of the anterior root-fibres. This agrees with the development of the fibres, since the spinal ganglia comprise the true parent-cells of the posterior roots. The degeneration of divided nerve-trunks has been successfully employed in vertebrates to discover the course of certain bundles of fibres within the central organ (spinal cord), by means of the easily-recognised alterations of the medullary sheath. The arrangement of the posterior columns of the cord has been very accurately determined by this method.

We have thus far assumed that a nerve-fibre must be perfectly homogeneous under normal conditions from its origin to its end, at all points of its course, *i.e.* that it presents no essential differences in regard to excitability and conductivity. This presumption is indeed not justified. We have long been in possession of certain facts which show that different parts of the nerve are anything but homogeneous. The sole gauge of

excitability is, of course, the reaction of the terminal organ as discharged by a stimulus of definite magnitude, and nearly all experiments bearing on this point relate to *electrical excitation of motor nerves*—the electrical stimulus being the sole test that is sufficiently accurate. The relations to be determined at any point of the nerve between magnitude of stimulus and magnitude of effect coincide in the main with those shown above to obtain in direct excitation of the muscle. If a tract of nerve is stimulated by gradually increasing single induction currents, it will be found that currents of which the intensity lies below a given limit ("liminal" value) do not excite, while with increasing current intensity the height of twitch is also augmented—the rise, according to Fick (40), being proportional within a certain range, while, according to Hermann (40), it is at first rapid and then more gradual. The connecting line between the summits of the single twitches would thus, according to Fick, rise obliquely to its maximum, according to Hermann it would form a curve concave to the abscissa.

Seeing that there is a discharge of potential energy in excitation of nerve, as in direct excitation of muscle, and indeed in any excitation of living matter, it is *a priori* evident that there can be no constant relation between strength of stimulus and effect. The excitability of a nerve can only be compared with other organs, or nerves, or different points of the same nerve, by employing the "liminal value" of the electrical stimulus as the (reciprocal) measure of excitability. Rosenthal (41) was thus able to establish the fact that the specific excitability of nerve-substance is greater than that of striated muscle, or, as it may be expressed, that *the indirect is greater than the direct excitability of muscle.* Rosenthal applied the sciatic nerve longitudinally to a curarised gastrocnemius. Induction currents were then led through both nerve and muscle, which, as the resistances of the two were approximately equal, were proportionately distributed between both sections, *i.e.* current flowed in both tissues at equal density. The indirectly excited muscle first began to twitch as the current was gradually strengthened by pushing up the coil, *i.e.* nerve responds to weaker electrical excitation. The results obtained by this method at different points of the same nerve are also of interest.

Budge (42) observed that "the sciatic nerves are more

excitable near the point where they leave the spinal cord than lower down, and at this last point again than at a still lower place, etc." He concluded that "greater force must be employed to evoke a twitch, in proportion as the seat of excitation is further from the spinal origin of the nerve, or (which is the same thing) nearer to its insertion in the muscle." He found, moreover, in the course of his experiments that certain points in the nerve "are much more excitable than others lying both above and below them, while others again are characterised by great inexcitability." These last he termed "nodal points." The excitation of one point of a nerve at a given strength of current will often discharge a perceptible twitch, while a point 1 mm. off, with the same strength of current, gives no sign of contraction. One point especially

FIG. 163.

noticeable in this connection lies in the middle third of the thigh, where the nerve gives off a large branch. Another such is commonly found near the starting-point of the motor roots. Pflüger (43) subsequently summed up all these facts in the dictum that "the same stimulus, applied in succession to two different points of the nerve, does not excite the muscle in the same degree; that excitation is the more effective which is applied at the point most distal to the muscle." The highest tract alone, next to the section, was relatively less excitable. According to Pflüger, the curve of excitability drawn from the nerve as abscissa would, therefore, resemble Fig. 163. There is a depression at the point where the branch is given off to the thigh. It is questionable whether the ordinates of this curve can really be regarded as a direct measure of excitability. It is evident that they express only relative magnitudes of stimulation-effects at the different points of the nerve, two explanations of the diminution towards the periphery being conceivable. Either the excitability of the nerve is greater in proportion as the point stimulated lies nearer the central organ, or the same stimulus calls out

the same strength of excitation at all points of the nerve, while the excitation itself increases with the distance from the motor organ (muscle). Pflüger decided for the last alternative, and concluded from the above facts that the excitation gathers strength in its passage down the nerve ("avalanche theory"), although the contrary would *a priori* be expected. The avalanche-like increment would, as Hermann pointed out (*Handbuch*, ii. 1, p. 113), justify the important conclusion "that conduction depends not simply upon an undulatory movement propagating itself from particle to particle, but upon the independent discharge of potential energy in the nerve, from which it follows that the transformed energy in each consecutive element of the nerve is slightly greater than in the preceding element." The wide bearing of this conclusion makes it essential that the underlying facts should be thoroughly sifted. Heidenhain (44) referred the cause of the greater activity of the higher tracts of divided nerves to the proximity of the artificial section. "The lower end of the nerve at once exhibits the same marked activity as the upper end, if a section is made lower down; excitability is raised near the section. The distance from the divided end is not, therefore, the determining factor in the magnitude of effect," and this applies to each stage of the survival of medullated nerve. The cause of this marked action from the cross-section will be discussed below, in considering the effect of electrical stimulation upon the excitability of the nerve.

Given that the unequal excitability of different points of the divided nerve is conditioned by the cross-section, there is on the other hand evidence to show that regular, local differences of excitability exist in the *undivided* nerve as well, the points at which branches are given off being in particular characterised by irregular excitability. According to Heidenhain (*l.c.*), excitability in the frog's sciatic is, as a rule, higher in the upper two-thirds than in the lower third. The curve shows a turning-point somewhat above the bifurcation of the sciatic into peroneal and tibial branches. It is lowest at this point, highest near the point of departure of the branches to the thigh (Fig. 164). Still more complicated, according to Hermann and v. Fleischl (45), is the curve of excitability of uninjured nerve, since the direction of the exciting currents is also of extreme importance to the magnitude of the effect. Descending induction currents are particularly effective at upper points of the sciatic, ascending

currents at lower points. V. Fleischl, indeed, makes the matter still more complicated by dividing the entire nerve into a number of segments, each of which is more susceptible to the descending current in its upper half, to the ascending current in its lower, and to both currents equally at the centre ("equator").

In view of these several experiments it seems *a priori* most probable that excitability in the normal nerve of the living animal is equal at all points of its course. Electrical excitation is really less fitted for determining this than chemical or mechanical stimuli. With the last, Tigerstedt (46) has actually ascertained the equal excitability of all points of the uninjured nerve. There is therefore no "avalanche" increment of excitation, or, at least, no fact is known which compels us to assume its existence.

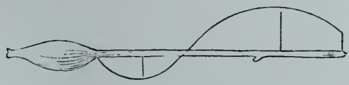

FIG. 164.—Curve of excitability along the sciatic nerve. (Heidenhain.)

Certain differences (which seem, however, to be caused less by local disparity of the true excitable substance of the axis-cylinder than by local irregularity of development in the investing medullary sheath) do nevertheless exist between the central and peripheral tracts of nerve. These are indicated not merely by histological evidence (Clara Halperson, 47), but also by the fact that the upper end of the frog's sciatic is more susceptible to the action of poisons (alcohol, etc.), than the deeper segments.

The observations of Clara Halperson show for electrical, and those of Efron (48) for other (chemical, thermal, mechanical) stimuli, that the responsive capacity in the upper segments of the nerve is greater in itself, and is raised more rapidly, and to a higher degree, by reagents which augment excitability, as well as by heat, than is the case in the lower segments.

The application of toxic substances, or of cold, again takes effect sooner in the upper segments. Efron found, *e.g.*, with two frog's nerves (of equal length and equal excitability), one of which was treated above, and the other below, with dilute amyl alcohol, that the excitability of the upper tract of the nerve disappeared completely, while that of the lower was still uninjured. In view of the intimate connection between excitability and conductivity, it is not remarkable that conductivity should be differently affected in the upper and lower parts, like excitability. According to Efron, who depressed the excitability of the middle

tract of the nerve by treatment with amyl alcohol, and compared its local capacity of response with excitability at two other points of the nerve, above and below, excitability diminishes in the first place more rapidly than conductivity, since (as in Grünhagen's experiment with local CO_2 narcosis) the excitability of the injured point is considerably reduced, at a time when it still appears to be unaltered at the upper point. At a later stage, on the other hand, there is an opposite reaction: conductivity is totally abolished, while local excitability persists in a low degree.

IV. Excitability in Different Nerves

All these facts regarding excitability of nerve-fibre relate to the usual frog's nerve-muscle preparation, *i.e.* gastrocnemius muscle and sciatic nerve. If we take the whole limb, and test the reaction of the other muscles supplied by the same nerve, with different strengths of current, the same intensity of stimulus does not throw all the muscles simultaneously into excitation; on the contrary, weak stimuli applied in the leg of the frog to the common nerve-trunk produce movement in one functionally co-ordinated group of muscles, *i.e.* the more excitable, while stronger excitation causes movement of another functionally combined, but less excitable, group of muscles. The first set comprise the flexors, as was pointed out by Ritter at the beginning of the century, the second the extensors. His often confused remarks, which are interwoven with the mystical speculations of the natural philosopher, culminate in the notion of an excitability "limited, conditioned, and finite" of the flexors, "unlimited, unconditioned, absolute" of the extensors. Ritter's conclusions have been frequently contradicted, amongst others by du Bois-Reymond, who refers to them in his great work as highly improbable, urging that they should be rejected until fresh and unimpeachable experiments should be forthcoming.

This task was undertaken in 1874 by Rollett (49), who rescued the investigations of Ritter from oblivion, and confirmed them by numerous experiments. He did not, like Ritter, employ the constant current, but a rapid succession of tetanising induction currents. With these it is easy to ascertain that minimal stimuli first send those muscles into tetanus which move the foot and tendon forwards and upwards, and also abduct the toes

(M. tibialis antic., peronæus, flexor tarsi anterior and posterior, M. extensores, abductores digit. and interossei); with stronger excitation of the common nerve, on the other hand, the extensors of the foot move backwards and downwards along with the adductors of the toes. The first group ("flexors") are mainly, if not exclusively, supplied by the peroneal nerve, the second by the tibial nerve, so that in this preparation (frog's leg) all, or at any rate nearly all, the fibres which subserve the antagonistic groups of muscles are found in the two primary branches of the common nerve. In subsequent experiments Rollett recorded the isolated contractions of the antagonistic groups of muscles, showing that only the flexors really contract at first, and not the extensors; increase of stimulus induces weak extension along with more pronounced flexion, and finally the extensor exceeds the flexor contraction. By making the antagonist muscles work against each other on the same lever (antagonistograph), and record the effects of this opposite action, Rollett finally convinced himself that when the nerve is excited, the flexors respond to weak stimuli with a greater yield of work than the extensors. The flexor movements increase with augmentation of stimulus up to a certain point, at which they are overtaken by the extensors; there is an intermediate stage of "struggle" between the antagonistic reactions. The same differences in excitability of flexors and extensors obtain in the rabbit (*cf.* Frl. Völklin, Hermann's *Handb.* i. 1, p. 113). Mechanical and chemical stimuli produce the same effect as electrical excitation (Osswald, 50). Osswald, by careful graduation of the shocks from an apparatus modelled upon Heidenhain's tetano-motor, succeeded (with minimal excitation of the nerve) in evoking flexor movements from frogs as well as toads, which changed to extensor movements on gradually increasing the stimulus. The extensors ultimately got the upper hand, and tetanus in extension made its appearance. The same effect was produced by chemical stimulation with sodium chloride and other salts.

Similar differences in the excitability of the nerve-muscle organ appear with other antagonistically working muscles. Grützner (51) found that during weak excitation of the vagus the constrictors of the glottis, during stronger excitation the dilatators, contracted. Fränkel and Gad (52) showed that the effect of gradually cooling the recurrent nerve was to cut out the

crico-arytænoideus posticus muscle earlier than the constrictor of the glottis, and Semon and Horsley (53) determined a peripheral, differentiating action of ether upon the laryngeal muscles in the same sense.

The differences of excitability in functionally differing nerve-muscle organs are, however, most striking in certain invertebrates, and most of all in the claw of the crayfish. Richet and Luchsinger (54) first observed that weak excitation of the claw-nerve opened, and stronger excitation closed, the claw. Fick (55), who had made objections (subsequently shown to be unfounded) to Rollett's first experiments on the frog's leg, tried to explain the observations of Richet and Luchsinger on purely mechanical grounds, as due to the anatomical relations of the excited muscles. This, however, was easily disproved (Biedermann, 56). If the claw-nerve is excited with the alternating current of an induction coil, by inserting two platinum points through the second or third joint (after arranging for the simultaneous graphic record of the changes of form in both antagonist muscles, by means of separate levers for each muscle) the same fact appears as in the normal uninjured claw, *i.e.* as a rule the abductor muscle contracts with weaker, the adductor with stronger excitation of the nerve.

When the current is strengthened by gradually pushing up the coil, the response to excitation being read off each time, it is found in a muscle free of tonus that the abductors alone react at a given distance of coil. With further strengthening of stimulus, the effects increase up to a certain limit, and then decrease and finally disappear, without any simultaneous change of form in the adductor muscle. The coils may then be brought much closer together without producing any perceptible excitatory effects in either muscle. The adductor muscle first comes into play at a given strength of stimulus, and responds to each subsequent excitation up to the maximum of current intensity, while the abductors give no perceptible reaction. The abductor, however, frequently contracts at the close of excitation, with the coil pushed home (Figs. 165, 166).

In every such case there is a certain interval of current intensity, during which neither of the antagonist muscles reacts to excitation from the nerve. The magnitude of this "neutral zone" varies in different cases. Moreover, it should be noted that

a neutral period, in the strict sense of the word, is not always demonstrable, and does not usually exist, as meaning an interval of current intensity at which neither muscle gives

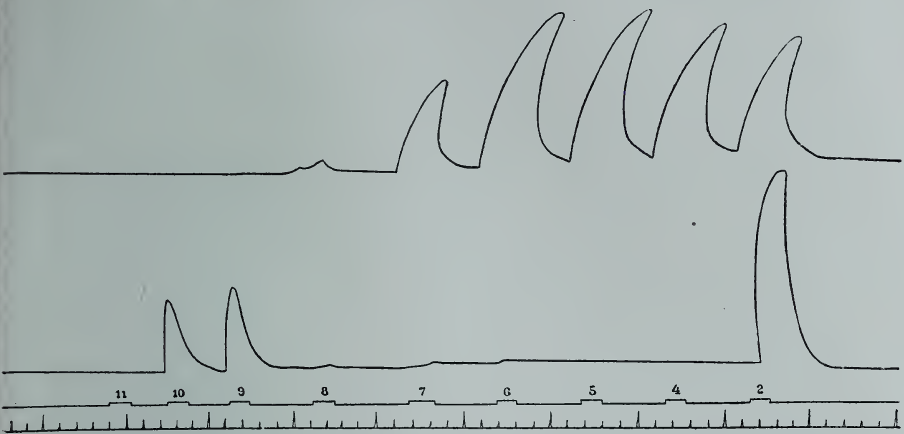

Fig. 165.—Contraction curves of adductor muscle (upper) and abductor muscle (lower) in the crayfish claw, excited from the common nerve with increasing strength of tetanising induction currents. The figures mark the distance of coil in centimetres.

any sign of response. There is always a given strength of excitation at which the contraction of both abductors and adductors is very feeble, but the stimulation is never wholly ineffective. In such a case a slight alteration of the secondary coil in one or the other direction suffices to elicit maximal contractions from either adductors or abductors.

In order to ascertain the presence or absence of a "neutral

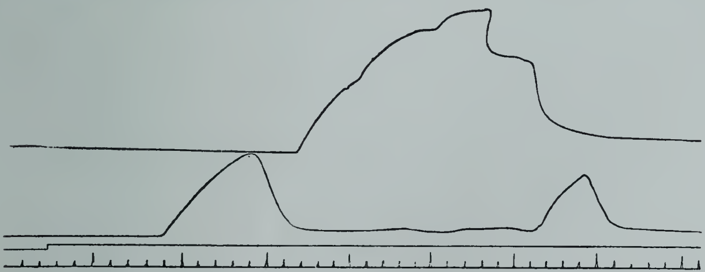

Fig. 166.—Contraction curves with indirect, tetanising excitation of adductor (upper) and abductor (lower) muscles of crayfish claw, with gradual approximation of secondary coil.

zone," it is convenient to excite the nerve continuously, while steadily pushing up the coil. The abductor muscle is first to

contract and relax again, after which follows the neutral period, or else the relaxation of the abductor is immediately followed by the contraction of the adductor (Fig. 166).

Although the alternation between the antagonist muscles is thus by no means such that the excitation of the one must inevitably exclude that of the other, this frequently is the case. And without exception, during maximal excitation of the adductor muscle, the abductor is quiescent, and *vice versa*.

The analogous effect of mechanical and chemical stimulation may be demonstrated here, as in the ordinary Ritter-Rollett phenomenon. It is always plain that the action of the abductor muscle preponderates immediately after cutting off the claw, while at the moment of amputation there is a rapid and transitory adduction.

Obviously there is here a complicated action of the mechanical stimulus upon the nerves of both muscles, which could only be analysed after further investigation; no less striking is the fact that, in the majority of cases, chemical excitation of the claw-nerve (by dipping a fresh section of the limb into concentrated NaCl solution) causes the action of the abductor to preponderate, although the adductor may be thrown into violent contraction by the same stimulant, as appears more especially when the abductor has previously been divided.

The innervation of the antagonist muscles of the crayfish claw is further complicated by the fact that each of the two muscles is undoubtedly supplied by inhibitory as well as by motor nerve-fibres, and these—as regards relations of excitability—behave in a diametrically opposite manner to the motor nerves. Both adductors and abductors usually exhibit a kind of tonus, which appears most plainly after dividing the antagonist muscle. If in such a case (after cutting through the abductor) the nerve of the limb is excited with alternating tetanising currents, while the secondary coil is gradually pushed up to the primary, the first effect of exciting the nerve will invariably be abduction of the claw, which under the circumstances can only be caused by the relaxation and consequent elongation of the *adductor* muscle. If the excitation is strengthened by gradual approximation of the coils, the same effect increases at first, until, at a certain and generally considerable intensity of current, each excitation causes a vigorous adduction of the claw which lasts throughout the

tetanus. If the excitation is weakened again, the opposite effect occurs, *i.e.* the muscle relaxes. With the gradual disappearance of the tonic contraction, the visible excitation effects appear in one direction only, namely, closure of the claw, *i.e.* contraction of the muscle. The same thing of course follows in preparations where the adductor muscle from the first manifests no perceptible tonus. In correspondence with the characteristics of this muscle as cross-striated, the changes of form described take place with considerable rapidity. If they are graphically recorded on a slowly-moving surface (Fig. 167), the curve sinks nearly at right angles at the beginning of the tetanus, when the muscle undergoes sudden and often maximal relaxation. At that strength of current with which the inhibitory excitation passes into its contrary, the effects are not seldom in both directions, and many irregularities are manifested.

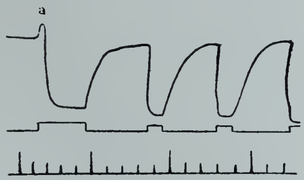

FIG. 167.—Tetanising excitation of adductor muscle of crayfish claw in persistent tonic contraction; succession of brief inhibitions (relaxation) at each excitation of the nerve.

In cases where the natural tonus is wanting, the inhibitory effect of stimulating the nerve may sometimes be demonstrated if the relaxed and resting muscle is artificially thrown into persistent or rhythmically interrupted excitation. This is easily effected by including a metronome in the secondary circuit, as well as the vibrating hammer of the coil, so that groups of induction shocks at any required rhythm may be sent into the adductor muscle by means of two platinum points thrust through the chitinous sheath of the claw. Regular rhythmical contractions are thus produced, which can be affected by simultaneous excitation of the nerve in the same way as the natural heart-beat, by excitation of the vagus. If, in the preparation in question, the adductor muscle is thrown into moderate persistent contraction by direct rhythmical excitation, and only oscillates, as it were, about its new position of equilibrium, in the rhythm of the metronome, a more or less rapid relaxation occurs at the commencement of inhibitory excitation of the nerve by tetanising induction currents (as in natural tonus). This is graphically expressed as a shallow inflection, or as a rapid fall of the curve, corresponding with complete relaxation of the muscle. In the first case (as nearly always happens with minimal excitation of the nerve), the magnitude of the rhythmical variations

usually remains unaltered, or at most undergoes some insignificant changes. With stronger excitation the result is otherwise. There will then be, along with the relaxation of the muscle and consequent fall of the curve, a perceptible and often considerable diminution in the height of the individual contractions, which does not necessarily entail an alteration in rhythm. This may be carried so far as to render the changes of form in the muscle quite imperceptible at the time of greatest relaxation, or at most indicated as slight undulations in the curve (Fig. 168). The tracings obtained from such inhibitory effects not infrequently exhibit a superficial resemblance to kymographic curves, which show the inhibitory action of the excited vagus upon cardiac movements.

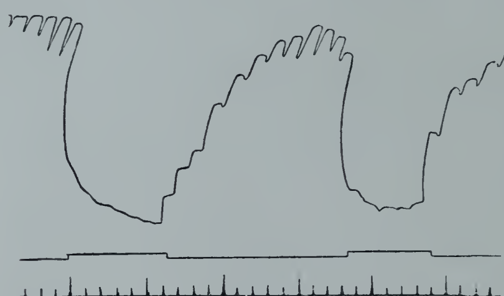

Fig. 168.—Inhibition of artificial contractions of adductor muscle of crayfish claw owing to stimulation of the nerve. The contractions were evoked by direct, rhythmic tetanisations of the muscle.

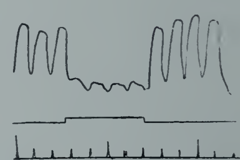

Fig. 169.—As in Fig. 168. Predominant diminution of single contractions.

From these observations we learn that diminution of the artificial rhythmical contractions proceeds *pari passu* with the relaxation of the muscle, and the same fact is even more evident in cases where the muscle has time to relax completely between two consecutive stimuli. The active inhibitory action then betrays itself only by a more or less considerable diminution of the single twitches, or (more correctly) short tetani (Fig. 169). Such a series of curves reminds us directly of the demonstrations of Heidenhain and Löwit, on the effect of minimal vagus-excitation on the rhythmical contractions of the frog's heart, where the first effect of inhibition is a diminution of the single beats.

The reaction thus described in the muscles of the crayfish claw (which can hardly be explained otherwise than by the antagonistic working of two opposite kinds of fibres passing by the same nerve-trunk into the adductor muscle) is by no means

without analogy. Pawlow (57) long ago communicated observations on the adductor muscles of the shell of *Anodonta*, from which it appeared that these are supplied by two kinds of nerve-fibres, one motor, subserving shortening of the muscle, the other inhibitory, running parallel with the first, and counteracting the shortened state of the muscle, so as to induce relaxation. By appropriate excitation, first one and then the other effect can be brought prominently forward. The crayfish claw is, however, better suited for this demonstration, since its muscles are striated, and the reaction follows incomparably quicker than in the smooth and sluggish molluscan muscles, in which, moreover, ganglion-cells are interpolated between the nerve and muscle, and are not easily excluded from interference.

Cardiac muscle is also subserved by nerve-fibres of opposite function and antagonistic action, which in many vertebrates run in a common trunk, in others again are separate, and bring out differences of excitability comparable in many respects with the above. Heidenhain (58), and later on Löwit, showed that minimal excitation of the vagus always resulted in inhibition, never (under these conditions) in acceleration, of cardiac activity. The latter only appears with greater strength of current, so that, under the presumption of two kinds of fibres, it may be said that the inhibitory nerves are more excitable than the accelerators. (Similar relations exist in warm-blooded animals—*vagus, accelerans* —*cf.* Meltzer, 58.) On the other hand, Löwit finds, *l.c.*, that the former are more easily injured by certain chemical reagents than the latter. If the vagus-trunk in the frog is treated with KNO_3 ($\frac{1}{4}$ %), there is a stage at which excitation of the nerve produces acceleration of cardiac activity only, while the same excitation below the part treated with potash is inhibitory. On washing the nerve with 0·6 % NaCl the potash-effect invariably disappears again, and this transformation of the vagus from accelerator to depressor may be repeated several times on the same preparation. Other substances (*l.c.* p. 493) have a similar action to KNO_3, as also vigorous cooling (ice). Alterations further seem to occur in the immediate vicinity of an artificial section, as expressed by a different ratio of loss of excitability in the antagonistic kinds of fibres. When Löwit placed the electrodes close together (1 mm.) upon the divided vagus, so that one was applied directly to the cross-section, there was invariably,

with given intensity and ascending direction of the single induction currents, a visible acceleration of cardiac activity, while reversal of the current was sufficient to produce inhibition. This is no doubt due to the fact that, as will be seen later, the excitation in the two cases actually occurs at different points of the nerve (in the first instance nearer the cross-section), where the different degrees of excitability thus give rise to different excitatory effects.

As the vagus-nerve of the frog contains distinct accelerating and inhibitory fibres, there are no less certainly differences of excitability in the same. It may further be concluded that the accelerating (augmentor) fibres are less excitable than the depressors, but more resistant to all processes that threaten to destroy the excitability of both kinds of fibres. This recalls the analogous relations of excitability in the vaso-constrictor fibres of a nerve-trunk that conducts both vaso-constrictor and vaso-dilator impulses.

At the same time it is not the functionally analogous fibres that agree in regard to excitability and resistance, since the cardiac inhibitory fibres agree with the vaso-constrictors, the cardiac accelerators with the vaso-dilators respectively. This contrast finds its most pronounced expression in the relations of excitability between the motor and inhibitory fibres of the antagonist muscles of the crayfish claw. From the above evidence we are forced to conclude that each of these muscles is supplied by two kinds of fibres (motor and inhibitory) which are functionally distinct, and differ in regard to excitability, not merely *quantitatively*, since the one effect invariably occurs before the other, in regular proportion with the strength of excitation, but also *qualitatively*, seeing that the inhibitory fibres of the one muscle correspond in their excitatory conditions with the motor fibres of the antagonist muscle.

Similar differences of excitability to those described above for centrifugal nerve-fibres seem to obtain in centripetal fibres also, as shown by the varying effects of excitation of the central end of the vagus, in proportion with the strength of stimulation. Two kinds of fibres have been determined in the vagus, which have an opposite action upon the respiratory centre; the one favouring inspiration, the other expiration, when stimulated. On exciting with induction currents, the intensity of which has been

graduated as carefully as possible, the first effect observed (in the rabbit) will in the majority of cases be the appearance of longer or shorter *expiratory* pauses, or arrest of respiration in the expiratory position, while stronger excitation always has an *inspiratory* effect. The marked expiratory action of chemical stimuli may depend upon their lower intensity. According to Meltzer (*l.c.* p. 385), there is ground for assuming in the vagus-trunk, as in the claw-nerve of the crayfish, four different kinds of fibres: *a*, inspiratory; *b*, inhibitory of inspiration; *c*, expiratory; *d*, inhibitory of expiration. Here, again, it is remarkable that there seems to be a gradation of excitability, resembling that in the claw-muscles, since the fibres inhibitory of expiration are most excited at a strength of stimulus which simultaneously excites the inspiratory fibres. At approximately the same strength of stimulus the inspiratory fibres are excited and their antagonists inhibited.

In all these cases (where with different intensities of stimulus there are obviously different effects in the peripheral and central organs supplied by the same nerve-trunk) it is a question whether the differences of reaction observed are due to corresponding differences in the excitability of the correlated nerve-fibres, or in that of the end-organ itself, or in both together.

In the cases observed by Rollett, he inclines to the view (since no such difference appears with direct excitation of the muscle) that the cause of the Ritter-Rollett phenomenon lies solely in the properties of the nerve, leaving undecided whether it derives only from the different excitability of the fibres destined for different muscles. Grützner (59), on the other hand, regards it as probable that these phenomena arise from actual physiological differences in the groups of flexor and extensor muscles, as well as in the entire nerve-muscle apparatus. He bases this upon a series of observations already referred to, which show a real physiological disparity between these groups of muscles, and further prove that the Ritter-Rollett phenomenon comes off after the exclusion of the nerves and nerve-endings by curare (*l.c.* p. 231).

The preceding discussion shows that there are great and almost insuperable obstacles to the comparison of the specific excitability of different nerves, since we are thrown back solely upon the reactions from the peripheral or central end-organs, which differ intrinsically in regard to excitability. And if this is apparent

even in functionally analogous end-organs, *e.g.* striated and smooth muscle, any comparison of the excitability of nerves connected with dissimilar terminal organs is fundamentally impossible. This is most plainly seen when the conditions for the discharge of *reflex* muscular contractions are compared with those for the *direct* excitation of motor nerves. The great differences apparent in the two cases can hardly be referred to specific differences in the nerve-fibres, but derive much rather from the inherent properties of the nerve-cells, as described above.

The most striking among many facts is that a single short stimulus, whether mechanical or electrical, inevitably discharges a twitch when the motor nerve of a striated muscle is stimulated directly, but by no means as certainly in the case of reflex excitation. Here, indeed, it is the rule that a single brief stimulus acts only (if at all) at very high intensities. That the cause for this lies not so much in special properties of the centripetal nerve-fibres as in dissimilar relations of excitability in the central reflex organs (nerve-cells) may be presumed from the above observations on conductivity of excitation in cells and fibres. We have seen that nerve-cells present a certain resistance to the conduction of the excitatory process, and thus to excitation itself,—expressed on the one hand by a more or less conspicuous delay in transmission, on the other by the greater susceptibility of the substance of the ganglion to short impacts of stimulation. At the same time, while the great sensitiveness of the nerve-cells to any kind of injury is very striking, it must be observed that in regard to excitability they resemble the less excitable, sluggish, smooth muscles rather than the quickly-reacting striated muscles. We shall see later how much the excitation of the more sluggish excitable tissues depends upon *duration* of stimulus, the most striking proof of which is perhaps the fact that the same induction shock which inevitably produces a twitch of the striated muscle when applied to its nerve, evokes no perceptible contraction of smooth muscles when sent into their nerve-fibres, and is as little able to excite a reflex twitch from the former. As regards the first, Langendorff (60) has shown that on exciting the cervical sympathetic with single induction shocks there is no perceptible change in the width of the pupil, whereas repeated shocks become effective by "summation." With increasing strength, however, Muhlert (61) was frequently able, even with

single shocks, to perceive a marked dilatation of the pupil, and Piotrowsky (62) also found this kind of excitation effective as regards constriction of the vessels of the ear. Still, the action of single shocks is extremely small, while tetanising excitation in both cases produces marked effects.

If the stimulation-frequency is altered, with constant strength of current, it is easy to show that the excitatory action (dilatation of pupil) is augmented, within a wide range, with increasing frequency. At an excitation interval of about two seconds Muhlert could not find any summation of stimulation - frequency, at a strength of 85·19 E, with even sixty-two consecutive stimuli. Where number and interval of stimuli are so arranged that an effect may be anticipated, the influence of strength of current may easily be determined, in the sense that mydriasis first begins above a certain range, and then with growing intensity rises to its maximum, at first rapidly, and afterwards more slowly. In this case the smooth muscle-fibres in which the summation occurs give a precisely similar reaction to that of the reflex centres of the spinal cord with excitation of the centripetal nerves. The more sluggish of the striated muscles seem to give a similar response. Thus Piotrowsky (56), on exciting the claw-nerves of the crayfish with single and intrinsically ineffective induction shocks, sent in at an interval of half a second, observed a weak contraction after every seven stimuli.

The striking insusceptibility of centripetal (sensory) nerves, or more correctly of their central end-organs, to single induction shocks has long been known.

Munk (63) pointed out that no reflex twitches were elicited from the frog by single induction shocks, impinging on a sensory nerve, unless it had previously been weakly strychninised.

Setschenow (64) also showed that induction currents with the vibrating hammer that were quite perceptible to the tongue discharged no reflex from the central end of the sciatic. In determining the upper limit of current intensity at which the animal remained undisturbed by single shocks, and the lowest intensity at which it was first excited with the vibrating hammer, he invariably found a great difference between the two, "because the sensory nerves (especially the central apparatus of transmission), which are so unsusceptible to single induction shocks, exhibit almost the same activity to a succession of shocks as the motor

nerves (or striated muscle)." The same fact appears also in the slender cutaneous (sensory) nerves of the frog's back, as shown by Fick (65). "When, instead of giving single shocks, the spring of the induction apparatus is set vibrating, no such enormous strength of current is required to evoke (reflex) muscular contractions." The same phenomena of summation have recently been investigated by A. Ward (66), who found in the brainless frog that the application of electrical stimuli, as nearly as possible uniform in quality and intensity, but not capable intrinsically of producing a reflex twitch, did after a certain number of stimuli evoke the same, if the excitation was repeated at intervals of about 0·5 sec. The required stimulation-frequency was about the same on raising the interval to 0·4 sec.

These, like all similar phenomena, can obviously be explained only on the presumption that a stimulus that is in itself ineffective produces a certain alteration in the nerve-cell (as in other cases in muscle, gland-cells, etc.), which is favourable to the production of an effective excitation, or rather is itself a weak excitation, and summates along with similar changes from succeeding stimuli, until an effective discharge is produced. Within the limits cited by Ward the time-interval is immaterial, as appears from the fact that the alteration caused by excitation is perceptibly of the same magnitude after 0·4 sec. In principle, these central summations are in no way dissimilar from those induced under certain conditions in the peripheral organs, and the nerve-cells only differ in degree from muscle, gland-cells, etc.

The same is sometimes expressed in a striking after-effect of tetanisation. After prolonged tetanisation of the divided spinal cord in the frog (near the cross-section), the same (descending) opening current that was formerly quite ineffective is often found to produce vigorous twitches, and this effect only dies out slowly after an interval of several seconds (Fig. 170). This phenomenon apparently stands in close relation with that termed by Exner "canalisation" ("*Bahnung*"), as opposed to "inhibition," in the antagonistic action of excitation within the central nervous system. If—as can hardly be doubted—we are here dealing essentially with alterations of excitability in the conducting elements of the gray matter of the lumbar region, an effect analogous to that of canalisation might also be expected in cases where the modifying and testing stimuli act in succession upon the two opposite poles

of the reflex centre, so that in the one case the direct excitability of the motor fibres of the spinal cord appears to be heightened, in consequence of a previous excitation of the central end of the sciatic, while in the other the reflex functions of the lumbar enlargement are favoured by previous tetanisation of the spinal cord. And it has, in fact, been found that single descending induction currents, which, when applied directly to a fresh section on the ventral surface of the frog's spinal cord, are *per se* ineffective, do produce marked excitatory effects after a prolonged reflex tetanus has been induced by excitation of the central end of the sciatic. Conversely, reflex stimuli that were formerly

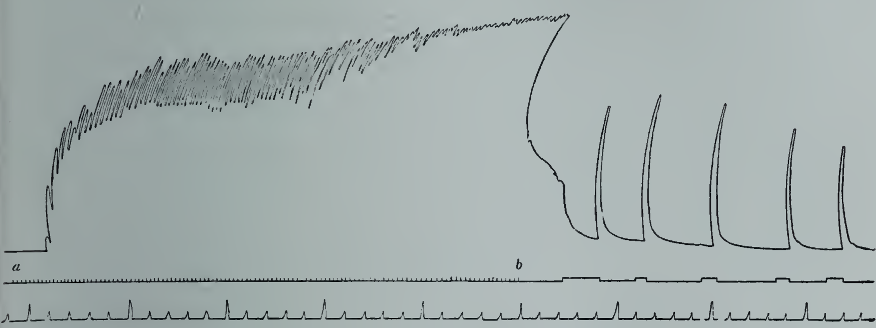

FIG. 170.—*a*, *b*, Incomplete tetanus of frog's gastrocnemius on excitation of the cord (divided above) with a rapid succession of induction shocks. Single and previously ineffective opening shocks then excite strongly, if led in at the part of the cord that has just been tetanised, by the same electrodes.

ineffective can be made to act by protracted and immediately antecedent tetanisation (Biedermann, 37).

V. Changes produced in Nerve by Activity

No less difficult than the establishment of the specific excitability of the nerve is the question *whether* (as seems *a priori* the more probable) *the course of the excitatory process in the nerve is associated with metabolism, and in what degree.* Two methods are here conceivable. It might be possible to demonstrate alterations in the chemical composition of the nervous substance either directly by means of prolonged excitation, or indirectly by investigating the laws of fatigue, and recovery, in the nerve. As regards the first question, it is even harder to decide this point in nerve than in muscle, owing partly to its smaller bulk, and partly

to the structure of the nerve-fibres. The sole functional, chemical alteration of nerve which, if not undisputed, is still maintained on experimental grounds, is its *reaction*. Immediately after du Bois-Reymond had established the functional alteration of the reaction in muscle, Funke (67) made a corresponding statement for medullated nerve, finding the cross-section both of peripheral nerve-trunks and of the more easily tested spinal cord of the curarised rabbit and frog to be neutral, while at a certain time after death, or in strychnin poisoning, they gave an acid reaction. Both assertions were disputed by Heidenhain (67), and confirmed by Ranke (67). According to Gescheidlen and Edinger (67), the gray matter of cord and brain is acid even in the fresh state, the white matter being neutral: Moleschott and Battistini invariably find the former more strongly acid than the latter, both during rest and during strong excitation. In direct contradiction of this, Langendorff (67) affirms that the central nervous system of the frog as a whole gives an alkaline reaction, and that the same is true of the living cerebral cortex of the rabbit or guinea-pig. Both in asphyxia and in anæmia, however, the reaction quickly becomes acid. The obvious contrariety of these statements is in large measure owing to the fact that the chief subject of experiment has been the excessively unstable ganglionic substance of the nerve-centres, the reaction of which alters with extreme rapidity. Pflüger, in fact, after even the most rapid washing-out of the brain with ice-cold physiological saline, observed an immediate *post-mortem* acidity of the gray matter. In view of the complete similarity of vital conditions in nerve-cells and fibres, it can hardly be found surprising that the metabolism of these two most essential structural elements of the nervous system should differ completely. In no case can the conclusions as to ganglionic parts be taken to gauge the reaction of *nerve-fibres*. Moreover, it is hardly to the purpose to take (as has usually been the case) a medullated nerve as the test of a final reactionary alteration, since only the substance of the axis-cylinder in these fibres can be counted as the essential physiological constituent. It is quite possible that the medullary sheath (which bears little direct part in the excitatory and conducting processes) may mask a real alteration of reaction at the cross-section.

As little as chemical alterations of the nerve-fibre have been established during, and in consequence of, excitation, can the ther-

mal processes be taken as proven. Neither Heidenhain nor Helmholtz, in spite of the great delicacy of their methods, was able to determine a reaction in peripheral nerve-trunks analogous to that of muscle; Schiff (69), however, recorded positive results. Here again it is necessary to distinguish between the ganglionic substance of the central organs and the nerve-fibres proper, and differences of thermal reaction must be expected in correspondence with the established differences of chemical reaction.

In view of the total lack of facts as to metabolism in the nerve-fibres, we are thrown back upon probabilities. The functional metabolism must under all circumstances (save in the gray matter of the centres) be very insignificant, as is proved *inter alia* by the poor supply of blood, as well as by the extraordinary tenacity of life, at least in medullated nerve-fibres. The same conclusion appears from the investigations into *fatigue and recovery* of nerve. The main difficulty here lies in the comparatively great fatiguability of the terminal organs (muscles, ganglion-cells) in which alone the capacity of reaction, or alteration, can be demonstrated. The existence of fatigue in nerve was for a long time assumed on quite insufficient analogies, since experiments on fatigue of brain, retina, etc., prove nothing as to the reaction in nerve-fibres. Bernstein (70) was the first who endeavoured to demonstrate fatigue of the persistently excited nerve in a nerve-muscle preparation.

In studying the effect of long-continued excitation of any point of the nerve upon its excitability, it is evidently essential to block off the stimulus, during the greater part of the excitation, from the terminal organ (muscle). Bernstein succeeded in doing this by sending a constant current through a part of the nerve between the point of excitation and the muscle. As we shall see, conductivity may be locally abolished without suffering permanent injury. From the reaction of the muscle after opening the insulating current, Bernstein formed conclusions as to the state of the muscle excited by the induction current. If the muscle no longer reacted to the constant stimulus at the free end of the nerve, Bernstein assumed a local fatigue, and computed its appearance at 5–15 min. Wedenski tried to obviate the injurious effect of the long closure of the battery current by sending in a strong ascending or descending constant current at the outset for a short time, so that the tract of nerve involved became incapable of conducting (70). Very weak currents then sufficed

to keep up this state. On breaking the current, the nerve almost immediately recovered its conductibility. Under these conditions Wedenski was unable to detect any fatigue in nerve at the point of stimulation, even after six hours' excitation. Maschek (70), who confirmed the experiments of Wedenski, succeeded in prolonging the experiment for twelve hours, without any perceptible fatigue of the point of stimulation. Maschek further showed by means of local ether-narcosis, which of course implies rapid recovery, that an excitation lasting many hours produces no visible fatigue at the point excited. Bowditch (70) arrived at the same conclusion in warm-blooded animals (cats) by means of curare, the effects of which are soon dissipated (*cf.* also Szana, 70). "When the action of curare has quite worn off after persisting three to four hours, the induction current, which has been passed uninterruptedly through the peripheral end of the muscle during the action of the poison, resumes its full effect."

The fact that nerve may be excited for many hours without perceptible fatigue suggests, as remarked by Bowditch, the idea that excitation may be transmitted *without consumption of material.* In view of certain facts to be considered later, it is, however, more accurate to say that a certain expenditure of nervous energy is consumed (even if it cannot be measured experimentally) in the mere propagation of the excitation.

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CHAPTER IX

ELECTRICAL EXCITATION OF NERVE

I. Law of Excitation by Electrical Currents (du Bois-Reymond)

The electrical current again ranks first among all the artificial means of nerve-excitation. A succession of experiments in this direction dates from very early days, and forms one of the most interesting chapters in physiology.

Du Bois-Reymond (1) has given an admirable historical survey of this part of the subject. At its outset we encounter the fact that *a motor nerve—like the corresponding striated muscle, but in a still higher degree—is apparently excited only at the moment of closing, or opening, a battery current.* In fact, du Bois' "general law of electrical excitation of nerve" was at first laid down for *indirect* excitation of the muscle, and was only extended at a later period to direct muscular stimulation. The law in its original form ran as follows:—

"It is not the absolute value of current-density in the nerve, at any given moment, that determines the response of the muscle, but the variations of this value from moment to moment: the stimulus to movement consequent on these changes being the more considerable according as they are (in a given interval) greater in magnitude, or more rapid in their onset."

If a motor nerve, still attached to the muscle, is laid across unpolarisable electrodes, and excited by the closure or opening of a sufficiently strong battery current, a single rapid twitch of the muscle appears at make and often at break also, after which it returns to the normal resting position. The most careful observation fails to detect any permanent shortening during closure, or

when the current is opened. The directly excited muscle of course gives a different reaction, inasmuch as it remains shortened, under certain conditions, during the passage of the current, and even for some time after it has been opened, though the contraction may be only local (persistent closing, or opening contraction). A visible persistent effect of current may also (*infra*) appear with indirect excitation of the muscle, both during closure and after opening the current. This is expressed in a more or less prolonged contraction of the muscle excited through the nerve, which may be continuous, or interrupted by single twitches, and which, from its resemblance to the tetanic form of contraction due to interrupted rhythmical excitation, is known as *closure*, or *opening, tetanus.*

Ritter (1798) was the first to point out that an indirectly excited muscle may, after prolonged closure of a powerful battery-current, fall, on breaking the circuit, into a state of persistent tetanic excitation—a manifestation named, after its discoverer, *Ritter's opening tetanus.* With this we shall have to deal later: for the moment it is sufficient to point out that nerve, like muscle, may, when a constant current is opened, fall into a protracted state of excitation, so that the opening tetanus and the persistent opening contraction are practically equivalent phenomena. A similar persistent excitation (as first remarked by Pflüger, 2) appears sometimes during closure of the current, and may be perfectly regular. Pflüger obtained this "tetanic" effect with quite weak currents; it increased up to a certain point with increasing intensity of stimulation, and then declined again. Under the most favourable conditions, *i.e.* with maximal excitability of nerve, closure tetanus makes its appearance at any effective strength of current. This is more especially the case with frogs kept in a low temperature for some time before making the preparation ("cooled frogs").

The excessive excitability of such preparations is a well-known physiological fact, and we shall frequently have to refer to it. It may be said, as a general rule, that the nerves of all frogs kept at a temperature below 10° C. will sooner or later acquire the property of being tetanically excited by constant currents (v. Frey, 3, Fig. 171).

Similar excitability is exhibited by nerves at a high temperature (Engelmann, 4), provided they are in a certain stage of dehydration (from evaporation, or treatment with NaCl). In both cases there

is sooner or later a *spontaneous* excitation of the nerve-fibres, as shown first in twitches of the fibrils and then in tetanic contraction of the entire muscle (*desiccation-* and *salt-tetanus*). If the excitability of such a nerve is tested from time to time with a current of uniform strength, it is found to increase, until, just before the commencement of desiccatory spasm, each closure, or opening, discharges powerful but irregular tetani. The closure-tetanus of " cooled " nerves, on the contrary, is usually quiet and regular, the curve showing no marked divergence from the tetanus-curve of intermittent excitation. The conjecture that closing and opening tetani are due to abnormal activity in the nerve, is completely contradicted by the fact that the motor

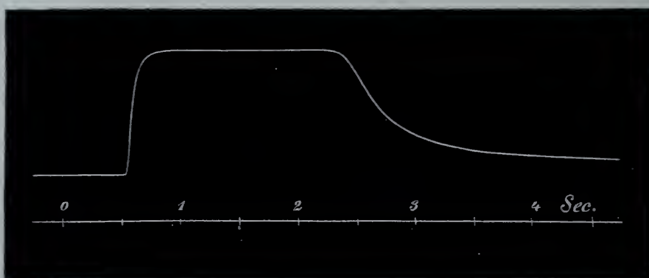


FIG. 171.—Tetanus curve of gastrocnemius on closure of a battery current (closure tetanus). Preparation from a cooled frog. (Von Frey.)

nerves of other animals invariably react by tetanus, under all circumstances. This applies, according to Eckhardt's observations (5), especially to nerves of warm-blooded animals, when excited with descending currents of average strength, as well as to the non-medullated motor nerves of many invertebrates (claw nerve of crayfish, etc., Biedermann). In both cases closure-tetanus is the rule and not the exception, and thus du Bois' "universal law" has as little application to indirect as to direct excitation of the muscle. We must rather hold that, although the visible effects of the transmitted excitation are fundamentally due to variations of density in the current flowing through the nerve, the excitatory process is locally initiated *throughout its entire passage*, and that other circumstances determine whether this continuous excitation is expressed at the peripheral organ (muscle) or no. The same applies to the state of activity at break of the

current. "Ritter's tetanus" is a direct proof of its persistence under certain conditions.

The similarity of effect in closing or opening tetanus, and in the true tetanus produced by discontinuous excitation, raises the question whether here too there may not be fusion of single, rapidly succeeding impacts of stimulation. In other words, does the steady constant stimulus during closure, or after opening, produce under the above conditions a discontinuous rhythmical excitation of the nerve; *is the tetanus of closure and opening a genuine tetanus or not?* We are familiar with the same difficulty (*supra*) in the previous question of whether the tetanic contraction of the muscle stimulated directly, or from its nerve, is really an unbroken process, or whether discontinuous invisible changes are masked by the apparent continuity. Ocular evidence is here inconclusive. We may indeed reason with apparent probability from the fact that every conceivable transition exists between irregular tetani broken by single twitches (clonic) and a perfectly steady (smooth) tetanus, and that these transitions must obviously consist of so many more single twitches in the time-unit, in proportion as they approximate to uninterrupted tetanus, that the latter, too, consists of fused twitches: and the trembling which concludes a long voluntary tetanus may equally be cited as evidence of its discontinuity. This, however, is insufficient proof.

In addition to the *form* of the muscle-curve, the *muscle-sound* and the *electrical reaction* of active muscle throw some light on the nature of a persistent contraction. As regards the first, the investigation of such a minute mass as a frog's muscle is obviously very difficult (the experiment has not yet been tried for warm-blooded muscle). And there has in fact been no result from the various attempts at transmitting to the plate of a microphone, or (according to Helmholtz's method) to consonant reeds, the vibrations during the period in which a frog's muscle is in closure-tetanus.

On the other hand, experiments with the capillary electrometer upon the electrical reaction of muscle have yielded more definite conclusions (v. Frey, 3), showing that closure-tetanus is in fact derived from a succession of discontinuous rhythmical impacts (10-15 per sec.); *ergo* nerve like muscle is thrown, during certain conditions, into persistent rhythmical excitation under the action of current flowing at constant density. (The inadequacy

of closure and opening tetanus to throw a second nerve-muscle preparation into secondary tetanus, as discussed in vol. i., has obviously no application as a counter-argument). Inasmuch as cardiac muscle and the ureter exhibit a similar reaction, this would seem to be a general law, applicable to all excitable substances. The time-distribution, *i.e.* succession of single excitatory impulses, differs of course in different cases, and exhibits a regular gradation. As a rule, therefore, and contrary to du Bois-Reymond's "universal law of excitation," it must be affirmed that the electrical current flowing at constant density gives rise (locally, at least) to *continuous* excitation, and the problem is rather why such excitation is not invariably transmitted; or, if transmitted, is not uninterruptedly expressed at the peripheral organ. The nature of the terminal organs is here undoubtedly of the first importance, as appears plainly from the *afferent* nerves.

The earlier electricians knew that centripetal impulses excited by the action of a constant current produce, in addition to a sharp make and break twinge, *constant* sensations, which may become insupportable with sufficient strength of current. It is true that the peripheral, sensible end-organs are nearly always coexcited, while there have only been solitary experiments upon the continuous excitation of sensory nerve-trunks by the direct action of the constant current. The fact (already known to Volta) of an excentric irradiation of pain so long as the electrodes are applied below the joint of the elbow, comes under this category. Grützner (6) further showed that both ascending and descending currents were effective throughout their passage, when the central end of the dog's sciatic was excited after previous curarisation, and division of the vagus on one side. A considerable rise of blood-pressure occurred at and during closure, with a simultaneous acceleration of pulse, which changed after opening the circuit, or at the end of excitation, into its contrary, *i.e.* slowing down of the pulse. Grützner found the same results on stimulating the central end of the vagus, with additional respiratory modifications, consisting in arrest of the diaphragm in expiration, or retarded respiration with expiratory pauses. The same observations have recently been confirmed and extended by Langendorff and R. Oldag (7). By gradually shunting the current into the nerve, they were enabled to observe its continuous action, and obtained,

with ascending direction, an expiratory slowing, or arrest, of respiration,—although a frog's leg included in the circuit was not once made to contract (Fig. 172).

The persistent excitation of *secretory* nerves by the constant current has been established on the frog's tongue, by the changes

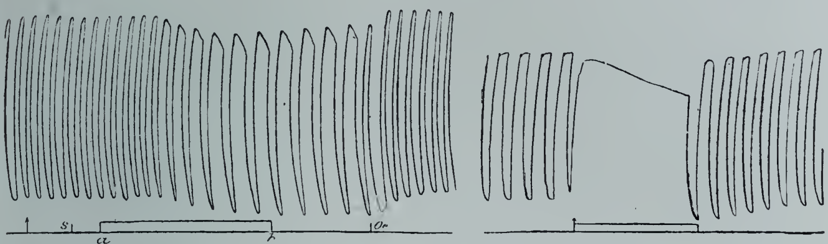


FIG. 172.—Respiratory curves (rabbit). Gradual shunting of ascending current into vagus. 1 Dan. (*S*) Closure, (*Oe*) opening of current. The rheochord slider was shifted from *a* to *b*. (Langendorff and Oldag.)

of the mucosa current during excitation of the glosso-pharyngeal (Biedermann, 8). In the *cardiac vagus* Grützner confirms the earlier conclusions of v. Bezold (*Unters. über die Innerv. des Herzens*, Leipzig, 1863, p. 72), since with a current of twelve pincus-cells the make and break only are effective, as shown by the following curve (Fig. 173).

Another proof that current excites not merely at the moment when it begins (or ceases), or during variations of density, but throughout its entire passage, is seen in the fact that at a given uniform strength of current a closure twitch only appears when the duration of current has outlasted a certain time (A. Fick).

FIG. 173.

This fact is already familiar to us in muscle—more particularly when non-striated—where it is easily determined. Its proof is more difficult in nerve, because the time-values involved are exceedingly small. While, *e.g.*, in smooth molluscan adductor-muscle the maximum effect of a given strength of current is not reached even with a duration of $\frac{1}{4}$–$\frac{1}{2}$ sec., the same, according to König (10), is obtained in excitation of the nerve after 0·017–0·018 sec. Under all conditions, therefore, we must allow for the fact that very brief closures of current produce no

muscular twitch during their action upon medullated, motor nerves. With increased duration of current beyond a certain point the twitches increase also, and reach their maximum with a relatively short closure, after which they cannot be augmented by any further prolongation of current or increase of intensity (provided an adequate strength of current is employed at the outset).

If we compare the susceptibility of different excitable substances to currents of brief duration, it will be found lowest in the non-fibrillated plasma of protozoa and in smooth muscle-fibrils, highest in medullated nerve-fibres; midway are cardiac muscle and striated skeletal muscle. This is well shown in experiments with single induction shocks, the effect of which agrees in the main with that of excessively brief constant currents. The medullated nerve of striated vertebrate muscle is peculiarly sensitive to this method of stimulation, the latter itself less so (especially when curarised), and smooth muscle still less, where in order to excite by single induction shocks an enormous intensity is often required. It is remarkable that the same graduated difference appears to exist between medullated and non-medullated nerve-fibres in regard to their susceptibility to single, brief currents (more particularly to induced currents), as between striated and smooth muscle. It is far less easy to elicit twitches from the claw-nerves of the crayfish with single induction shocks than with the constant current.

We must now consider the second postulate in du Bois' "universal law of excitation," by which he affirms that a positive or negative variation of current must always be of a certain abruptness in order to excite, and that (with otherwise uniform conditions) the excitation appears more certainly, and within a certain range more strongly, in proportion as the variations of intensity are more sudden in their onset.

Whatever application this may have to medullated nerves in connection with twitching, striated, vertebrate muscles, it is by no means a universal law, appropriate to *all* excitable tissues. Nothing is easier than to show in the usual frog's nerve-muscle preparation (the "physiological rheoscope") that even the weakest electrical currents may excite, provided they are adjusted sufficiently sharply, *i.e.* that the intensity of variation is as steep as possible. The peculiar susceptibility of these nerves towards even a trace of frictional electricity is due to the presence of

currents of exceedingly rapid onset, and induced currents have a powerful excitatory action, even at low intensity, from the same reason. This tendency of the ordinary nerve-muscle preparation to react to the weakest currents, provided they are adjusted with sufficient rapidity, renders it a valuable indication of the presence of weak currents of brief duration (action currents in the muscle).

An interesting fact in this connection, and one that also depends mainly upon the influence which the onset of any current exerts upon its excitatory action, is the unequal effect of the make and break shock from an induction apparatus. The excitatory action of the make shock is without exception much lower than that of the break. This is plainly seen when the secondary coil is a long way off from the primary. There is always a point at which the break shock is effective, when the make shock fails to excite; on approximating the coils, the latter also takes effect.

Since, as is easily shown on the galvanometer, the quantities of electricity in the make and in the break shock are equal, the dissimilarity of physiological effect must be fundamentally due to the differences in time-distribution of the two induction currents, caused by the appearance of the extra current on closure of the primary circuit. Since the primary current in the last case does not at once reach its full strength, but increases gradually, while it suddenly disappears on opening the circuit, the induced current must rise more abruptly at break than at make of the primary circuit (Fig. 174). Accordingly, the break shock gives a sharp "crack" in the telephone, the make shock, on the contrary, yields a dull, weak sound (Grützner).

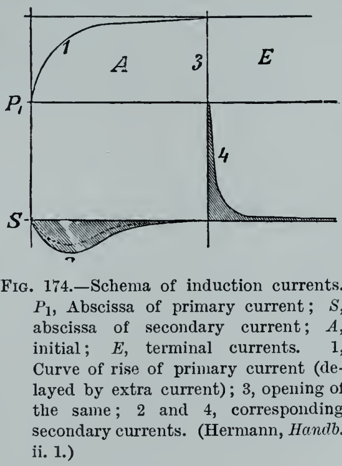


FIG. 174.—Schema of induction currents. P_1, Abscissa of primary current; *S*, abscissa of secondary current; *A*, initial; *E*, terminal currents. 1, Curve of rise of primary current (delayed by extra current); 3, opening of the same; 2 and 4, corresponding secondary currents. (Hermann, *Handb.* ii. 1.)

This inequality of physiological action in the make and break shocks, as due to inequality of time-distribution, is very inadequately compensated by the contrivance of "Helmholtz's side wire," which is attached to most induction coils, and there have been later attempts at producing induction currents by other means, better

suited to experimental requirements. Hering (11) made the secondary coil rotate round a vertical axis in front of the primary, which was traversed by a constant current, giving rise to uniform induced currents—since, with the coils at right angles, induction is at zero, and with other definite inclinations of the coils corresponding definite induction currents make their appearance.

Grützner (12) subsequently investigated the physiological action of currents from a Stöhrer's machine, in which two wire-coils with iron axes revolve in front of a powerful horse-shoe magnet. Each revolution yields four currents, corresponding as two pairs in respect of time-distribution. If *S* and *N* (Fig. 175) are the poles of the magnet, and *I* and *II* the coils

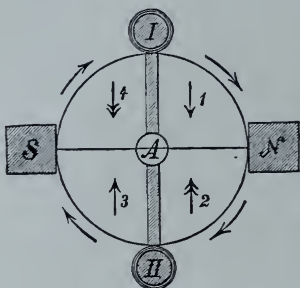


Fig. 175.

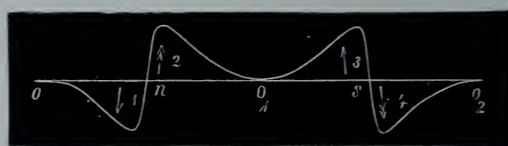


Fig. 176. (After Grützner.)

rotating round the axis *A*, then when they have shifted $\frac{1}{4}$ revolution clockwise from this position, so that *I* is opposite *N*, the first current rises *gradually* from 0. If *I* is then moved away from *N*, the falling current alters instantaneously in the reverse direction. Rising suddenly, it gradually falls to zero, and then rises again equally gradually to its former height, as the coil *I* travelling through all three quadrants approaches *S*, the south pole. This is succeeded by an abrupt rise of current in the reverse direction, so that (as shown by the accompanying curves, Fig. 176) two gradually and two abruptly rising currents appear with each revolution. This can be elegantly demonstrated (after Grützner) if the platinum-point electrodes are drawn at uniform speed over paper moistened with iodide of potassium during the revolution of the apparatus. The resulting electrolytic curves appear as lines which are correspondingly thicker at the apexes of the curves than in the rest of the tracing. The gradually rising currents are represented by lines, small at first, and after-

wards broader, while the abruptly rising currents give the reverse, the decomposition being marked at first and subsequently diminishing (Fig. 177). While investigating this electrolytographic method Grützner also found that the steeply rising break induction current of an ordinary du Bois' sliding apparatus had a far more marked electrolytic action than the gradually rising make induction current.

In the frog's nerve-muscle preparation, with low intensity of current, abruptly rising currents are always the most effective (now one and now the other, according as the electrodes are situated on the nerve). On increasing the current, a second smaller twitch appears, corresponding with the other steeply rising

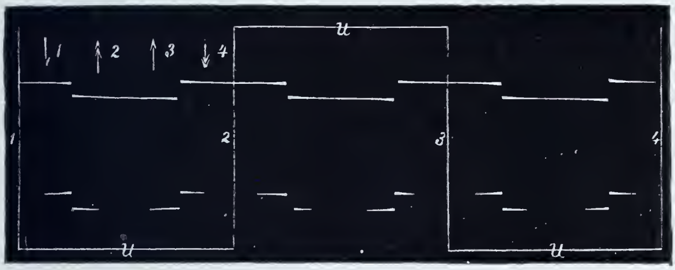


Fig. 177.

(and opposite) current. Further increase of current intensity complicates the excitatory effects still further, since with an ascending direction of current the anodic inhibition becomes apparent. In rare cases, all four induction currents may excite, and there are then at each revolution two strong and two weak twitches, alternating as one strong and one weak twitch. The most significant result of Grützner's investigation is *the predominant action of the abruptly rising currents*, where the direction is again of importance, inasmuch as (according to the observations of Hermann and Fleischl, *supra*) the upper portion of the nerve is first excited by descending, the lower portion by ascending currents, while they both take effect at the "equator" only. It is with much higher intensities of current that the gradually rising currents also become effective.

The beneficial influence of great abruptness of oscillation is shown *inter alia* by the fact that even very strong currents may be shunted into the nerve without perceptible signs of excitation,

provided only that the increment accrues gradually and evenly. The same thing is, as we have said, still more easily established in muscle.

If the action of make and break induction currents is investigated in the nerve-muscle preparations of other animals, very different results are arrived at (as recently pointed out by Schott, 13), showing once more how unjustifiable it is to lay too much stress on facts derived from experiments with one kind of animal.

In the nerve-muscle preparation of toads Schott (13) found the steeper break induction shocks relatively less effective than in

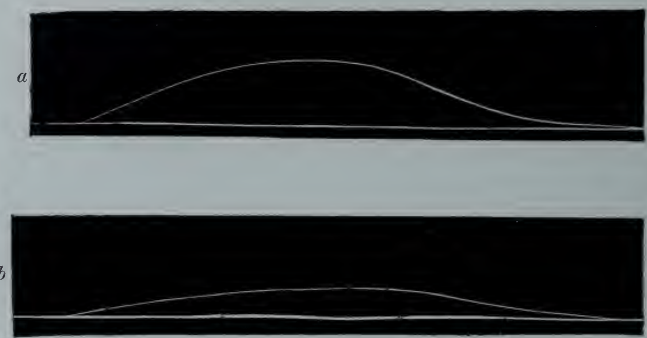


FIG. 178.—Toad's gastrocnemius. *a*, Make induction twitch ; *b*, break induction twitch. (J. Schott.)

the frog; there is hardly any difference in the distance of coil at which the make and break shocks take effect. While the indirectly excited frog's muscle always describes much higher twitches (of medium size) if break shocks are employed, this is not the case with the toad, and the make shocks may even be the more effective (Fig. 178). According to Grützner (14), single induction shocks of different time-distribution can also be produced as follows. A ring of sheet-iron is fastened to a brass disc in the form of Fig. 179. This consists of two parts, *M* and *N*, of which the latter (on rotating the disc to the right) rises gradually from its base *H* upon the brass-plate to its greatest height, while *M* is cut off in the direction of the radius of the disc. If the ringed iron piece *MN* is then rotated between the poles of a horse-shoe magnet, surrounded with wire-coils, there will (on turning the disc to the right) be a constantly increasing part of

the iron ring from the point *H* between the poles of the magnet, the magnetic force of which is correspondingly diminished. This slow decline in the magnetism corresponds to a magnetic induction current in the coil, which rises the more slowly as the iron ring increases more gradually in thickness, and as the disc is the more slowly rotated. On the other side the part *M* of the ring induces, under similar conditions, by its sharp edge, an almost instantaneous ascending current. In the frog-preparation the current from the sharp tooth (like the break shock) is always more effective than that from the obtuse tooth, while this is reversed in the toad, where the slowly ascending current invariably excites more effectually than the sharp rise (Fig. 180).

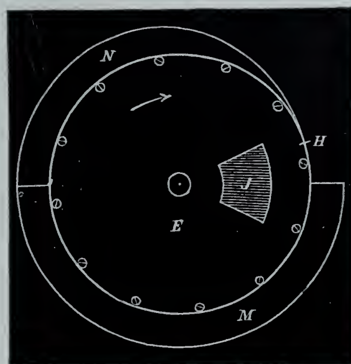


Fig. 179.

It is a question whether this is due merely to the known sluggishness of toad-muscle as compared with that of the frog, or whether there are actual differences in the nerve-fibres implicated. In any case du Bois-Reymond's dictum, that current excites not in virtue of its actual density, but from the rapidity of its variations, is not applicable to all locomotor apparatus. The rapidly twitching muscles of the frog correspond with the

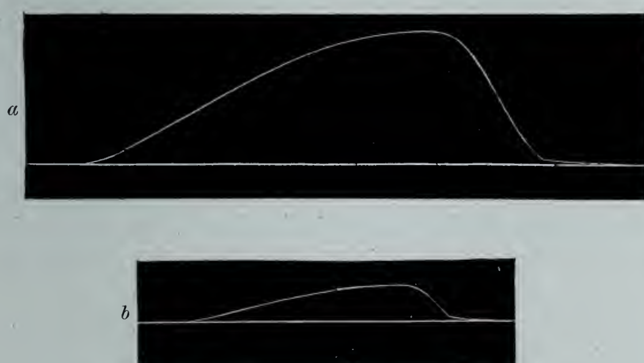


Fig. 180.—Gastrocnemius of toad. Twitches on excitation with *a*, obtuse tooth; *b*, sharp tooth.

law, the muscles of the toad do not, and it applies even less to the more sluggish contractile tissues (smooth muscle, many Protozoa, etc.). "Since in these, from their sluggishness, a given physiological state is more than usually prolonged, they are especially adapted for stimuli of long duration and gradual onset." To borrow a comparison from Grützner (14, p. 384), it is with these as with the movement of heavy sluggish masses impelled by external momentum. "If we shoot a bullet against a large heavy wooden door, turning easily on its hinges, the ball passes through, without pushing the door on the hinge. But if the same amount of energy as is contained in the moving bullet is directed against the door by increasing the mass of the ball while its velocity is diminished, then such a ball will readily turn the door on its hinges. Thus an induction shock of abrupt onset injures a sluggish (smooth) muscle without causing contraction, while the same quantity of electricity distributed over a longer period may excite a vigorous twitch, without injury." Slow moving stimuli are thus, according to Grützner, the adequate incitation for slowly developing processes.

The different physiological action of the make and break induction shock again appears to rest, not *solely* upon differences of time-distribution, but also upon the still obscure dissimilarity of electrolytic effects. Grützner (14) found that currents of abrupt onset, including break induction currents, have a much stronger electrolytic action than those which commence more gradually. This would account for the fact that, in direct excitation of homogeneous striated or even smooth muscle (*e.g.* the adductor muscle of the shell of *Anodonta*), the contraction discharged by a break shock is usually the most conspicuous, *i.e.* makes its appearance earlier.

These facts lead us to anticipate that the *form* of the curve of oscillation of an electrical current is not without effect upon the excitatory action; and the first essential for determining this point is that we should be able at will to modify and vary the nature of the increase of intensity (or density) in a battery current. The problem of raising a galvanic current in a circuit from zero, by different degrees, to a certain final value, was first attacked by v. Fleischl (15).

He succeeded by means of his "orthorheonome" in producing increment and decrement of the exciting current at any uniform

desired rate—within a certain range, and in exact proportion with the time-interval. The apparatus, which is constructed on the principle of Wheatstone's Bridge, consists essentially of a homogeneous circular conductor (trough filled with $ZnSO_4$ solution). The current is led in at *a b*, the opposite ends of a diameter. A

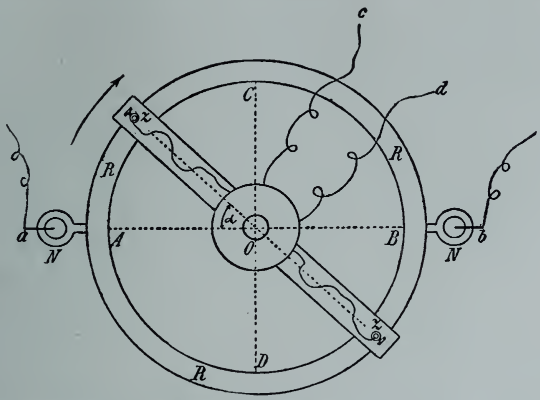


FIG. 181.—Schema of v. Fleischl's orthorheonome. (Ellenberger, *Physiologie*, ii.)

metal conductor turning on its centre runs across diametrically (Fig. 181, *zz*), its two points with amalgamated zinc terminals dipping into the trough *R*. The nerve is included in the circuit of this rotating diameter (between *c d*). As often as it is in the direction of the entrance points of the current *AB*, a certain fraction of the current will pass through it; while at an angle of 90° (at *CD*) this fraction = 0. The current through the nerve diminishes regularly with the magnitude of the angle (*a*), provided

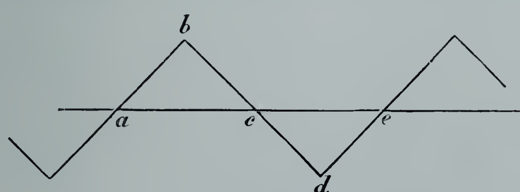


FIG. 182.

the resistance of the circuit is otherwise vanishing. Von Fleischl showed that, with regular rotation of the rheonome, the oscillations of current might be expressed in a broken line similar to Fig. 182. Equal sections of the abscissa correspond with equal times, while the ordinates are proportional with strength of

current. The ordinates above the abscissa correspond with descending currents in the nerve, those below the abscissa with ascending currents. The curve (*abcde*) corresponds to an entire revolution of the bridge.

It is obviously easy to determine by this method the amplitude, duration, and abruptness of the oscillation within wide limits; it is also possible to lead a current into the nerve which shall correspond only with the tract (*abc*). The action of a single linear oscillation of current was investigated by Fuhr (15), using a similar apparatus to that of v. Fleischl. No special differences from the ordinary method (in which current intensity rises, as it were, with infinite steepness) could be detected in the indirectly excited muscle-twitch. Von Fleischl always saw the twitches first at a certain rate of rotation of the rheonome, *i.e.* at a given pitch of current oscillation. They do not last throughout the entire period of increase of intensity, but commence at a certain pitch, and soon terminate, while the curve of oscillation increases still further, and finally sinks abruptly. The sharp turning-points (kinks) of the curve are not excitatory. The reaction of the muscle during the entire period of current oscillation is thus comprised in a single contraction.

Von Kries subsequently constructed a "spring rheonome" on an entirely different principle, by which he obtained linear variations of current of different steepnesses, while the resulting intensity remained constant, producing oscillations of the form . If *ab* (Fig. 183) is a solid or fluid conductor traversed by a constant current, there will at any two points be a difference of potential proportional to the distance between them. If *c* and *d* are then joined by a conductor, the resistance of which as compared with the resistance of *cd* is very high (nerve, *e.g.*), it will be traversed by a current of which the intensity can easily be raised lineally as required, if—as is the case in v. Kries' apparatus—one leading-off electrode is firmly attached to the point *c* while the other slides with constant rapidity along the wire *ab*, and is finally brought up at a certain point of the conductor (Kries, like Fleischl, employed a trough of fluid) traversed by the current.

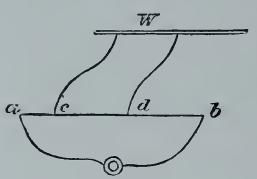


FIG. 183.

Von Kries agreed with v. Fleischl that the twitches discharged by "time-stimuli" (*i.e.* linear variations of current) are not usually distinguishable from those due to "instantaneous stimuli." In single cases, however, we meet with notable exceptions, the twitches from time-stimuli being much more extended. Yet it must be remembered that the mechanical changes of form in the indirectly excited muscle-twitch give a very incomplete representation of the true time-distribution of the excitation at the point where the nerve is directly excited. So that when v. Kries concludes from his experiments that a linear variation of current in one direction excites the nerve for a brief period only, this would seem to be as little justified as the postulate of a universal law of excitation, based upon observation of the make and break twitch.

As a rule, in order that a time-stimulus may evoke as high a twitch as an instantaneous stimulus, the intensity (i_s) finally reached at a given pitch (D) must exceed the intensity of the momentary stimulation (i_m) for the same effect. This different ratio $\left(\frac{i_s}{i_m}\right)$ for each value (D) is termed by v. Kries the stimulation quotient. It increases of course with increasing values of (D), and affords a direct gauge of the diminution of excitatory effect caused by the extension in time of the oscillation. In the frog's nerve-muscle preparation v. Kries found it almost invariably greater than 1. In other cases, however, strong time-stimuli yielded larger twitches than were usually produced by momentary closures. This seems to be the rule in sluggishly reacting excitable substances. A stimulation quotient is naturally not to be obtained in such cases. The integral dependence of the nerve upon the nature or mobility of its constitution is clear from the observation of v. Kries, that cooled nerve reacts better to lower, warmed nerve to higher oscillation-pitch.

It is noteworthy, as first pointed out by v. Fleischl, and confirmed by v. Kries, that rheonome twitches do not readily evoke secondary contractions. Secondary action only appears with very strong supramaximal stimuli. V. Kries also observed stronger effects in the capillary electrometer with time-stimuli, along with simultaneous failure to excite the secondary preparation. It is plain that the wave of oscillation is differently distributed in instantaneous and in linear excitation, the latter being characterised

by less steepness of pitch and more extended time-distribution. We may affirm without hesitation that nerve and muscle are thrown into a much more protracted state of excitation by linear variations of current of a finite pitch than by momentary stimuli.

The same may be true of physiological innervation. The strikingly low rate of oscillations of the muscle-current, as noted by Lovèn, both in strychnin-tetanus and in voluntary innervation, on the capillary electrometer, makes it probable that a complete tetanus may none the less occur in the frog's muscle, while induction shocks must act at considerably greater frequency to produce the same effect.

II. Influence of Direction upon the Exciting Efficiency of Currents

In addition to pitch, density, and duration, as well as kind of increase, of the exciting current, the effect of electrical excita-

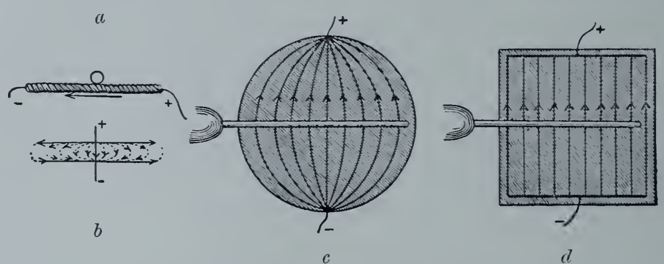


Fig. 184.—Schema for the transverse excitation of nerve. (Hermann.)

tion of the nerve depends, as in muscle, upon *direction of current*, with reference both to arrangement of fibres and to peripheral organ at the working end of the nerve. As regards the former, it was known to Galvani that transverse passage of current through a motor nerve at—as nearly as possible—right angles to the axis of the fibres produced no effect. Galvani bridged the nerve across a moist and not very thick thread (Fig. 184 *a*), through which he led a constant current. In consequence of the narrow path of the current through the nerve, there are comparatively few opportunities for the formation of longitudinal components, though these are by no means entirely excluded. On the other hand, it is doubtful whether any considerable fraction of the current traverses the nerve, unless very strong currents are made

use of. Since, however, these do produce vigorous twitches, the conclusion for transverse inexcitability of nerve, based upon observations with weaker currents, seems to be insufficiently established. Hitzig (16) and Filehne (16) employed two strips of clay, mixed with 1 % salt solution, for leading in the current. The broad thin edges of the clay strips were applied on both sides to the nerve, and the strength of current appropriately graduated. Here again there was inexcitability to transverse passage.

As in muscle, the best method is to lay the nerve in an "exciting chamber" filled with indifferent conducting fluid (physiological saline), through which the current is sent from two opposite points or surfaces (Fig. 184). The results and conclusions of the several experimenters are, notwithstanding similarity of method, very divergent. A. Fick, jun., (16) affirms the complete inexcitability of nerve to pure transverse passage of current, confirming du Bois-Reymond's conjecture (16), that with approximately equal conditions the influence of the angle at which the current passes must be about equal to its cosinus. Tschirjew (16), on the contrary, denies the influence of the current angle, and regards the excitability of the nerve to transverse and longitudinal passage of current as equal. It is important to remember that (as was first pointed out by Hermann, 17) the resistance of nerve is very different in the longitudinal and transverse directions, being much higher in the latter than in the former. If a layer of parallel frogs' nerves between two square glass plates is traversed by current, first lengthways and then across, the transverse resistance, as measured by Wheatstone's method, is found to be about five times as great as the longitudinal resistance (according to Hermann, the first exceeds the resistance of the mercury by $12\frac{1}{2}$ million times, the second by only $2\frac{1}{2}$ million). Similar differences exist in striated muscle, and appear in both cases to be bound up with the normal vital properties of the tissue, since they diminish considerably after mortification has set in. (According to Hermann, the ratio in nerve sinks, even with heating to 50° C., from 1 : 5 to 1 : 2 – 4.)

With regard to these facts, it is clear that when the nerve enclosed in the exciting chamber is longitudinally traversed, a greater fraction of the current must pass through it than when the lines of current are in the transverse direction, and it only

remains to be seen whether this fact is sufficient to justify Tschirjew's assumption. On purely theoretical grounds this is *a priori* improbable, while experiments carried out under Hermann's direction by Albrecht and A. Meyer (16) are distinctly against it. From the first point of view we have the fact that both in the pseudopodia of Rhizopods (*Actinosphaerium*), and also in striated muscle, inexcitability to currents directed vertically to the long axis of the cells is indubitably established. Since there is general conformity between nerve and muscle in their reaction to current, it would be surprising if there was any exception in this particular. Albrecht and A. Meyer showed, moreover, that with pure transverse passage of current through the nerve, the strongest battery and induction currents had no effect, although the least displacement of the nerve caused a twitch. Starting with certain experiments already described on locally alcoholised nerve (which indicate that excitability rises within the tract involved, while conductivity is simultaneously diminished), Gad and Piotrowsky (16) have recently reaffirmed the transverse excitability of nerve, urging as proof that the local increase of excitability from alcohol is more conspicuous in a preponderatingly transverse passage of current (through a trough between two clay strips connected with unpolarisable electrodes) than with the longitudinal direction. Without entering into detailed criticism it may be said that this experiment hardly suffices to throw over the older conclusions as to transverse inexcitability of nerve.

The differences of excitatory effect, according as the current flowing longitudinally through the nerve is directed to or from the terminal organ, belong to a department which has been explored from every point of view since the first days of galvanism. A solution and a legitimate interpretation have, however, only recently been attempted. We know as a general law that a constant electrical current flowing through a motor nerve excites mainly at closure or opening of the circuit, although the passage of current at constant density may also have an excitatory effect upon the muscle. Along with this fact we know that the magnitude of make and break twitch, and even the appearance of one or the other, is also conditioned by *direction* of current in the nerve, *i.e.* whether it flows from a point proximal to the muscle to a more distal point, or *vice versa* in a descend-

ing direction. We cannot linger over the earlier discussions of the matter, which for the rest have been admirably and exhaustively summed up by du Bois-Reymond. It is sufficient to state that (after Pfaff had pointed out certain regular differences in the action of ascending and descending currents) Ritter was the first to formulate a "law of contraction"—as subsequently confirmed by Nobili. It will be seen from the following table that, apart from direction of current, the temporary excitability of the preparation plays a great part in the effects of stimulation.

Ritter-Nobili's Law of Contraction

Stages of Excitability.	Ascending Current.	Descending Current.
I. (Ritter)	M. contraction B. 0	M. 0 B. contraction
II. (Ritter)	M. contraction B. weak contraction	M. weak contraction B. contraction
III. (Ritter) I. (Nobili)	M. contraction B. contraction	M. contraction B. contraction
IV. (Ritter) II. (Nobili)	M. weak contraction (0) B. contraction	M. contraction B. weak contraction
V. (Ritter) III. (Nobili)	M. 0 B. contraction	M. contraction B. 0
VI. (Ritter) IV. (Nobili)	M. 0 B. 0	M. weak contraction B. 0

Ritter distinguishes six, Nobili four, stages of excitability. The completely contrary effect of homodromous currents at the first (highest), and later (Ritter's fifth), stages of excitability is very striking. Nobili denies it and asserts that there is only one marked twitch for each direction of current, the opening twitch of ascending, the closure twitch of descending currents. More recently there have been various attempts to determine the facts which underlie the law of contraction, as well as a theoretical explanation of them. An important step was taken almost

simultaneously by Heidenhain and by Pflüger, who pointed out that the "law of contraction" was a function not merely of *direction of current* and of *excitability*, but also of *current intensity*. Beginning with the weakest currents, Heidenhain (18) obtained the following table of effects from freshly-prepared nerve:—

Strength of Current.	Descending Current.		Ascending Current.	
	Make.	Break.	Make.	Break.
I.	0	0	C	0
II.	0 (rarely contraction)	C (rarely 0)	C	0
III.	C	C	C	0
IV.	C	C	C	C

Heidenhain does not seem to have exceeded a certain average strength of current, for Ritter's fifth stage (and Nobili's third), (*i.e.* closure twitch only with descending, opening twitch with ascending direction of current, in the fresh nerve), do not appear. All later observers state that at a given medium strength of current both closure and opening are effective, with both descending and ascending directions. It is only with stronger currents that the contrary effect of opposite direction of current becomes apparent. In regard to minimal currents, on the other hand, there are considerable differences of opinion. Heidenhain noted as the first contraction the closure twitch of the ascending, as the second the opening twitch of the descending current, while most later observers give the closure twitch with both directions of current as the first effect of minimal currents (Bibliography to Herm. *Handb.* ii. 1, p. 61), the only difference being whether the descending or ascending current was the first to act. The formula given by Pflüger (2) must undoubtedly be accepted as the most correct expression of the law of contraction—

Strength of Current.	Ascending Current.		Descending Current.	
	Make.	Break.	Make.	Break.
Weak	C	0	C	0
Medium	C	C	C	C
Strong	0	C	C	0 (weak contraction)

In fresh, vigorous, motor frog's nerves the closure of weak currents therefore effects a twitch with both ascending and descending direction of current, while the opening of the current remains without effect in both cases (first stage of the law of contraction). The opening contraction then makes its appearance gradually with growing intensity of current, so that the second stage is characterised throughout by twitches from the muscle, which accompany the closure and opening of both ascending and descending currents. The opposite effect of a contrary direction of current first appears when the intensity has exceeded a certain limit, the rule being then universal that only *the closure of descending and opening of ascending currents* elicit any contraction, while closure of ascending and opening of descending currents invariably fail in effect. These consequences are so regular that they can be employed as a means of determining the direction of current physiologically, upon a rheoscopic preparation. In order to demonstrate the law of contraction it is essential whenever possible to test upon the same preparation the effect of different strengths of current in *one* direction only, without changing the position of the nerve upon the electrodes, the most convenient method being to excite two nerve-muscle preparations from the same frog simultaneously, by laying the two nerves in opposite directions across the same unpolarisable electrodes. It is then possible to observe at the same time all the changes in the reaction of the muscle which follow upon increased intensity of current, as when, in the third stage, one preparation twitches only on closing the current, the other on opening it.

Pflüger was the first to give any satisfactory explanation of the facts (at first sight very striking) which underlie the law of contraction. There is first of all the marked contrast between make and break effects in the third stage. It is obvious that the mere alteration in direction of the electrical current is not *per se* a sufficient explanation, and if, as can hardly be doubted, the nerve is also excited at closure of the ascending and opening of the descending current, the failure of the excitation can only be explained by the fact that it is in some way hindered from expressing itself in the muscle. In other words, there must at some part of the tract of nerve traversed be an alteration which blocks the excitatory process on its way to the muscle, at closure in the one case, on breaking the circuit in the other.

In view of the experiments on striated and smooth muscle as discussed above, it is natural to conjecture for nerve also that we are in presence of antagonistic polar effects of current, in the sense that the excitation is from the kathode only at closure, from the anode on opening the current. When, therefore, at closure of a strong descending current, or on opening a strong ascending current, there is a twitch, it is evident that there is nothing in either case to block the transmission of the excitation from the corresponding electrode to the muscle. When, on the contrary, the break twitch fails to appear in the first instance, the make twitch in the second, it may be assumed with probability that the kathodic excitation discharged above the anode with ascending direction of current is blocked there, and never reaches the muscle. And conversely the break excitation, discharged with a descending current above the kathode, appears to die out at the previously kathodic point of the nerve. Thus, in the precise analysis of the phenomena consequent upon the electrical stimulation of motor nerves, we reach the same ultimate conclusion as for contractile substances, viz. that the current does not discharge the process of excitation equally, at all points of the area traversed, but produces "polar" alterations, manifested partly as excitatory and partly as antagonistic inhibitory phenomena, as expressed in the third stage of the law of contraction. We are indeed less favourably situated here than in the direct excitation of contractile substances, where the polar action of the current is immediately translated into corresponding changes of form at the physiological pole, since we are thrown back in nerve upon the reactions of the terminal organ (more or less remote from the seat of stimulation), in proof that the change usually takes place in one direction only.

The fundamental importance of the postulate of polar excitation by current, which Pflüger at first deduced simply as an inductive consequence of the law of contraction, rendered it desirable to obtain further direct evidence of its accuracy. V. Bezold (19) attempted to confirm the law by time-measurements for motor nerve, as he had for striated muscle. The method, which in both cases consisted in measuring the latent period of the muscle-twitch, proved to be even simpler for indirect than for direct excitation of the muscle. If an ascending current of medium density is led through a sufficiently extended part of the nerve in a nerve-muscle preparation, the latent period of the

make twitch must obviously be much longer (if the excitation is discharged at closure of the current from the kathode, distal to the muscle, thus having a longer course than the anodic opening excitation) than the latent period of the break twitch under otherwise similar conditions. The contrary must occur with a descending current. The difference corresponds in either case with the time required by the excitation to propagate itself through the intrapolar portion. These presumptions are confirmed by the results of v. Bezold. The interval between the moment of excitation and commencement of the muscle-twitch is greater at closure of the ascending, and opening of the descending, current than it is conversely.

Further evidence, at least for the localisation of the changes in the nerve that underlie the break excitation, was brought forward by Pflüger himself, when he showed that a Ritter's opening tetanus manifested under favourable circumstances with descending direction of current disappeared as soon as the nerve was divided in the middle of the intrapolar tract, the muscle being thus removed from the influence of the anode. This experiment does not of course come off in a Ritter's tetanus with ascending direction of current.

In order to explain the phenomena comprised under Pflüger's law of contraction, we are experimentally forced to assume that the electrical current, along with the excitatory action proceeding at make from the kathode, at break from the anode, elicits simultaneous inhibitory action, the localisation of which can only be conjectured. If by analogy with the excitatory process we regard the inhibitory effect also as polar, we should *a priori*, on the analogy of the muscle, presume that changes take place in the substance of the nerve—at the anode at closure, at the kathode on opening the current — as expressed in a more or less pronounced depression of excitability and also of conductivity. All the phenomena of the law of contraction are satisfactorily explained on this hypothesis, with the aid of the further postulate that the development of excitation and of inhibition are not perfectly parallel, since weaker currents suffice, as a rule, to produce the former, than are required to elicit the latter. We can thus understand why currents of medium strength should evoke both closing and opening twitches, with either direction of current. The inhibition which they discharge

at the anode or kathode respectively is manifestly insufficient to neutralise the excitation approaching the muscle, from the kathode at make of the ascending current, from the anode at break of a descending current. While, lastly, the single reaction on stimulating with weak ascending or descending currents is readily explained on the assumption that the magnitude of the two impulses excited by current is unequal—the fall of the current in particular being the weaker stimulus. With gradually rising current intensity, the more active kathodic stimulus at make is first to take effect, and the weaker anodic opening stimulus only comes into play when the current is still further strengthened.

III. Changes in Excitability and Conductivity produced by the passage of a Galvanic Current (Electrotonus)

We have next to consider the facts from which it is concluded that an inhibitory impulse arises at the anode on closing, at the kathode on opening, a constant current. It is again to Pflüger that we are indebted for decisive evidence. While in the muscle, polar inhibition finds double expression in change of form, along with simultaneous depression of excitability, we are in nerve thrown back solely upon the latter, and should therefore (according to the previous observations) expect, with sufficiently strong currents, to find depression of nervous excitability at the anode during closure, at the kathode after breaking the circuit. Here we are at once confronted by a marked dissimilarity from striated muscle. While in the latter, "electrotonic" changes of excitability are essentially *local* and confined to the physiological poles, in medullated nerve (under similar conditions) not merely the whole intrapolar, but considerable sections of the extrapolar region also, exhibit alterations of excitability during and after the passage of current, these alterations being unlike and opposite in the vicinity of the two poles. Even the earlier electricians observed indications of such a reaction on sending current through an entire limb, but Eckhardt was the first to show by unexceptionable experiments that a nerve of which a portion was traversed permanently by a constant current, underwent substantial modifications as expressed by increased or diminished excitability to artificial stimuli at points of the intra- and extra-polar regions.

The former is universally the case on the side of the kathode, the latter on that of the anode. In a typical series of experiments (the results and theoretical conclusions from which form the contents of the classical work on "Electrotonus" so frequently alluded to), Pflüger has exhaustively investigated all the facts which relate to this subject.

If a constant current is led, by means of unpolarisable electrodes, into the middle portion of a nerve that is still united at one end with the muscle, the resulting alterations of excitability are easily demonstrated in the tract of nerve that lies between muscle and polarising current. As "test-stimulus" we may employ either an easily graduated electrical, or a chemical, or mechanical excitation, the height of the muscular contraction being of course the gauge of excitability. If increase of response is to be demonstrated, the twitch discharged by the test-stimulus before the polarising current is made must obviously be submaximal. When the latter is ascending, and the stimulus is applied at a point of the nerve not too remote from the anode, in the direction of the muscle, a more or less definite depression of excitability inevitably appears, which increases in magnitude with increasing strength of the polarising current. Under these conditions a current that previously discharged a maximal twitch may become totally ineffective, and in the same way a vigorous tetanus produced by electrical or chemical excitation (concentrated salt-solution) may be momentarily interrupted if a strong ascending current is closed above the part excited. If different points of the "myopolar" portion of the nerve (between muscle and polarising current) are excited as equally as possible, it can easily be determined that, on the one hand, the depression of excitability spreads with increased intensity of current over an increasing portion of the myopolar region, while, on the other, the degree of alteration from the anode diminishes rapidly. With a descending polarising current, the relations of excitability within the myopolar region are precisely opposite in character. The response is now augmented under all circumstances, in a greater degree in proportion as the test-stimulus is nearer the kathode, and the polarising current (other conditions being equal) stronger. Tetanising stimuli, which previously elicited little or no trace of excitation, evoke a vigorous tetanus, when a descending current of sufficient strength is made above the point at which the nerve is excited.

The relations of excitability in the extrapolar ("centropolar") tract of nerve *above* the ascending or descending polarising current are much more complicated, particularly in the first case. The augmentation of excitability still appears indeed (as pointed out by Pflüger) with weak currents, but quickly passes into its contrary with stronger excitation, since at a certain strength of polarising current a stimulus of given intensity discharges a weaker contraction than was previously the case, while at last the strongest stimuli (which excited maximal twitches before the closure) fail to give any effect. This, however, is due less to declining excitability above the kathode, *i.e.* centropolar diminution of excitability, than to decreased excitability and conductivity below, at the anode, which becomes more and more prominent with increasing strength of polarising current, and modifies in a greater or less degree the action of every excitation discharged from above upon the muscle. This is the principal reason why Valentin and Eckhardt failed to detect the extrapolar increase of excitability *above* the kathode. We must accordingly assume a constant increase of excitability, proportionate with strength of current, above the ascending as well as below the descending current: as in the latter, it is the more pronounced the nearer the point tested lies to the polarised tract of nerve; at a definite distance from the kathode (according to the intensity of the current) it is 0. The extrapolar excitability above the anode of the descending current is again in complete conformity with the anodic alterations of excitability which appear below the ascending current. There remains only the excitability within the intrapolar tract that is actually traversed by the ascending or descending current. Obviously, whatever has been stated above of muscle under the same conditions, both as regards difficulties of investigation and method adopted, must hold good of nerve also.

Starting with the erroneous presumption that an induction-current excites the entire tract of nerve through which current is passing, Pflüger attempted in the first place to determine the "total excitability" of the intrapolar tract, as dependent upon the strength of the polarising current,—leading in the induction current employed as test-stimulus by the polarising electrodes (according to a method previously employed by Eckhardt), as was described above for muscle. But since *polar* action has now been determined for induced currents also, it is clear that the results of these

experiments cannot be accepted in the original sense. Pflüger himself has made certain experiments with chemical excitation of single points of the intrapolar tract of the nerve which show it to be divided into two sections, separated by an "indifferent point"—in one of which excitability is depressed, while it appears to be raised in the other—the former occurring in the vicinity of the anode, the latter in that of the kathode. With increasing strength of current the indifferent point shifts from the region of the anode to that of the kathode (independently of the direction of the current) in a higher degree in proportion with the strength of the polarising current. The anodic depression of excitability spreads in this way with increasing strength of current over a constantly enlarging area of the tract of nerve traversed. These facts, as to alterations of excitability in the intrapolar tract, have been recently confirmed by Tigerstedt (20) with mechanical single stimuli, since his observations coincide entirely with all the other results of Pflüger.

The *after-effects of the constant current upon the excitability of nerve* (among the immediate consequences of which must be reckoned the break excitation itself) are no less important than the alterations of excitability which appear during the closure of the polarising current. Here again certain isolated researches date from the first days of galvanism, and have been carefully summarised by Pflüger (*Electrotonus*, p. 72 ff.): these refer mainly to the conditions of appearance, and to the interpretation of the opening excitation. But, as Pflüger pointed out, the after-effects of the passage of current are expressed not merely in visible excitatory phenomena, but also in regular alterations in response at all those parts of the nerve which manifested changes of excitability during the passage of the polarising current. This may be briefly expressed by saying that there is, generally speaking, at all points where a rise of excitability is apparent during the passage of the current, a diminution of response immediately after the opening of the circuit, and *vice versa*. It should be added that the positive modification (increase of excitability) on both sides of the kathode of the polarising current is only *temporarily* reversed at break, and finally terminates in a new increment of excitability, while the negative modification (depression of excitability) in the region of the anode undergoes a *permanent* positive modification, and subsides as such. The

duration of the first phase of decline of the kathodic alteration of excitability (negative modification) is shorter, other conditions being equal, in proportion as the polarising current is strengthened, so that it is sometimes difficult to demonstrate (Obernier, 21), and can only be shown when the test-stimulus acts simultaneously with or immediately after the opening of the polarising current. Otherwise the intensity and duration of the after-effects depend entirely upon the intensity of the original changes, including of course strength of the modifying current.

From these facts, therefore, we learn that, when a tract of medullated nerve is continuously traversed by a constant current, the nerve falls not merely at and between the electrodes, but also beyond the poles, into an altered state (*electrotonus*), as manifested, apart from other phenomena to be described below, in alterations of excitability towards given stimuli, in the sense that there is, while the current is passing, an increase of excitability in the region of the kathode, a depression of excitability in the region of the anode. The term *katelectrotonus* is commonly applied to the former state, the term *anelectrotonus* to the latter, though it should be remarked of both expressions that they cover not merely the alterations of excitability, but also the modification of the nervous substance produced by an electrical current in the region of the two poles,—which, as we shall see, may find other modes of expression.

The electrotonic alterations of excitability may be clearly shown in a graphic representation. If the excitability of each point is drawn as ordinate upon the nerve as abscissa, the line which unites the tops of the individual ordinates usually (apart from the increase of excitability near the cross-section) forms a line parallel with the abscissa. If current is then led through the middle portion, there will be increased excitability on the side of the kathode, diminished excitability on that of the anode. If the former is represented by an ordinate drawn upwards (positive), the latter may be similarly drawn as a downward line (negative). The excitability declines from either point, both between and beyond the poles, and spreads over a larger tract of the nerve as the polarising current becomes stronger. Let *gi* (Fig. 185) be the nerve, to which are applied the electrodes *A* and *B*; the excitability of single points during closure to weak, medium, and strong currents may be expressed by the three curves *abc*, *def*,

and *ghi*. Here again the true form of the curve is uncertain, and this merely represents the general relations. The curve *abc* shows that nearly the whole of the intrapolar tract is thrown with minimal currents into a state of augmented excitability (katelectrotonus), while the indifferent point in this case is near the anode. Excitability increases gradually from this point on the one side, while on the other it is correspondingly diminished. The alteration reaches its maximum in the immediate proximity of the two electrodes, whence it declines again to 0. The curve (*def*) from currents of medium strength is essentially the same, but is distinguished by the larger tract of nerve which it embraces, and by higher ordinates, while the indifferent point lies about midway in the intrapolar region. These differences correspond

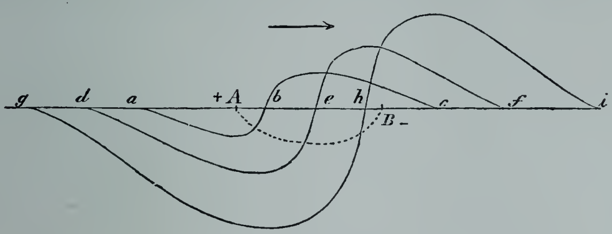


FIG. 185.

with the fact that the electrotonic alterations of excitability increase in intensity and extent of diffusion with the strength of the polarising current. The same applies to the curve (*ghi*) of strong currents, which contrasts with *abc*, inasmuch as the indifferent point lies near the kathode, so that almost the whole intrapolar tract is in a state of anelectrotonus. It would also be easy to record the after-effects of an- and katelectrotonus, since the excitability of every point, at all events immediately after breaking the current, is exactly opposite to the effect at closure.

We have up to this point considered only the effect of *strength* of polarising current upon magnitude and diffusion of electrotonic alterations of excitability, yet, as Pflüger has shown, the *length of tract* traversed, as well as the time-relations of the passage of the current, are not unimportant factors. The first of these two (besides the older experiments of Humboldt, Ritter, and others) was investigated by du Bois-Reymond. According to Ohm's law, the intensity of an electrical current is directly proportional with its E.M.F. and inversely proportional with the

resistance of the circuit. If the effect of length of tract upon excitation, or upon electromotive alterations of excitability, is to be studied, care must be taken, in view of the great resistance of nerve, that the total resistance is not unduly altered with the enlargement of area traversed. Du Bois-Reymond accomplished this by introducing an alcohol rheostat as resistance, against which the resistance of the nerve-tract is practically minimal. He then found that the extrapolar electrotonus (*i.e.* its galvanic manifestation), and the negative variation as the expression of excitation, were more strongly developed when the intrapolar tract was lengthened. Pflüger subsequently reached the same conclusions.

Willy (22) then tested the different magnitudes of twitch under uniform conditions. He employed two nerves, traversed one in longer, the other in shorter portions by current. Stronger excitation of the longer portion was found to be effective with the closure of descending currents only, while closure of ascending currents gave the contrary effect. Willy formulated his observations as follows: "Excitability is *cæteris paribus* the stronger, in proportion as the muscle is nearer the kathode, and farther from the anode."

Marcuse (22) investigated the same problem under Fick's direction, the nerve being placed in a small parallel-epipedic glass trough filled with physiological saline. Its opposite walls were made of amalgamated zinc, through which an induced current was led in. As a longer or shorter portion of the nerve was bathed, it was traversed by the current at constant density; with increasing length the minimal, just effective strength of current diminished, at first rapidly and then more slowly, "appearing to approach a limit asymptotically, or after passing a minimum to increase again." With the constant current also, Marcuse found a beneficial effect from a longer intrapolar tract, with both ascending and descending direction of current, since the first perceptible twitch made its appearance earlier than in a shorter tract. Tschirjew (16) and Clara Halperson (23) arrived at much the same results.

The time-development of all the modifications in the nervous substance which are characteristic of electrotonus, including the above alterations of excitability, will be discussed at a later period. Pflüger places the katelectrotonic increase of excitability im-

mediately after the closure of the battery current, from which point it declines slowly, while anelectrotonus is relatively slow to develop and to diffuse; the maximum invariably occurs some time after closure. We shall see that this agrees perfectly with the galvanic alterations of the nerve in electrotonus.

If conductivity is, in the words of Gad, only the expression of "longitudinal excitability" in the nerve, *i.e.* capacity of transmitting a local excitation longitudinally from section to section, it seems *a priori* highly probable that it should undergo alterations of conductivity coextensive with the electrotonic alterations of excitability. The law of contraction indeed indicates directly that the persistent anelectrotonus (with ascending direction of current), as well as the diminishing katelectrotonus (with descending direction of current), do cause an inhibition of conductivity as regards the excitation approaching in the first case from the kathode, in the last from the anode. It must further be assumed, in view of the first and second stages of the law of contraction, that the depression of conductivity effects an active inhibition only with relatively high strengths of polarising current. Von Bezold's admirable investigation (19) of conductivity in electrotonised nerve only corresponds partially with these presumptions. It has been stated that every excitation discharged above a tract of nerve traversed by an ascending or descending current remains without effect at a certain strength of polarising current, because the diminution of excitability (and conductivity) is presumably so considerable in the entire anelectrotonic tract, that it offers an actual hindrance to the propagation of the stimulus to the muscle. Before this point is reached, however, this betrays itself in a more or less considerable delay in the entrance of the muscle-twitch, which is greater in proportion with the strength and duration of passage of the polarising current. In order to determine exactly the share taken by the polarised tract, the two poles, and also the extrapolar tract of nerve, v. Bezold in the first place stimulated the muscle directly, and then the nerve at three different points (a, b, c) of its course, by a single induction shock (Fig. 186). It was then possible from the differences of latent period to calculate the rate of conductivity of the excitation from a to the muscle, from b to a, and from c to b. An ascending battery current was then led uninterruptedly through the tract c, the secondary coil of an

induction apparatus being included in the circuit, when the finally retarding influence of the extrapolar anelectrotonus upon the rate of conductivity appeared on repeating the four twitches. This occurred in fact without exception: apart from the influence of duration of closure (as already mentioned), the value of this retardation at each cross-section of the nerve was greater in proportion with its proximity to the positive pole of the polarising current. If this result can hardly be regarded as surprising,

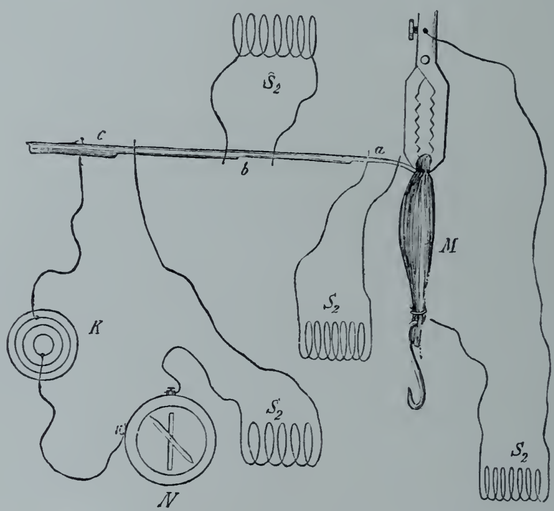


FIG. 186.—Influence of electrotonus upon conductivity in nerve. (v. Bezold.)

since it agrees perfectly with the reaction of excitability at the single points of the extrapolar tract of the nerve as described above, v. Bezold's further observations are at first sight very remarkable. He finds a similar reaction of conductivity when the polarising current at *c* is descending, the myopolar tract of the nerve being therefore in katelectrotonus. In view of the contrast expressed in all other relations between anelectrotonic and katelectrotonic alterations of the nerve, we should *a priori* expect the contrary, *i.e.* acceleration of conductivity, or no alteration. The fact is, however, less surprising when it is remembered that v. Bezold employed very strong constant currents, and prolonged the closure for thirteen minutes. Under these circumstances the polar katelectrotonus of the muscle is also expressed as a pronounced depression of excitability and of

conductivity, which long outlasts the opening of the polarising circuit (local fatigue). Rutherford (24) indeed has shown, with weaker polarising currents and shorter closures, that conductivity is retarded in anelectrotonus only, while it is accelerated in katelectrotonus; it is only with strong currents or longer closure that such acceleration passes into its contrary. It had previously been pointed out by Hermann (25) and Grünhagen (25), and also by Werigo (25), that with longer closure of strong currents the initially augmented excitability of the kathodic points of the nerve gave way to a gradually developing inexcitability, which may amount to complete impenetrability to excitation with even the strongest induction shocks. This state develops in the muscle proportionately with the strength of the polarising current, and may make such a rapid intra- and extra-polar entrance that it is hardly possible to demonstrate the transitory rise of excitability. With weak currents, on the other hand, it is hours before this secondary alteration in excitability makes its appearance. If the polarising current is opened at the moment at which the kathode becomes impenetrable, excitability (conductivity) returns almost instantaneously—to disappear again with renewed closure of the current. V. Bezold attempted to draw conclusions as to conductivity within the intrapolar tract itself, and assumed an indifferent point, halving the area traversed by the current (its position being independent of strength of current), from either side of which conductivity diminished regularly towards both poles.

In immediate connection with these changes in the excitability of nerve during the electrotonic state, and its direct after-effects, there is a whole series of excitatory and inhibitory phenomena which must be briefly considered. The opening excitation was referred to above as an after-effect of the passage of current, in Ritter's sense, *i.e.* a reaction of the nerve to certain alterations produced by the current. Ritter expresses himself characteristically as follows (*Beiträge zur näheren Kenntniss des Galvanismus*, i. p. 78 ff., 1802): "We have stated that the phenomena which accompany the removal of battery-currents are of peculiar significance. In justification of this assumption we need only emphasise the fact that they appear at the instant in which the organic body and its constituents are withdrawn from the influence of the battery. Hence they are in no way the im-

mediate product of the battery, for how could this engender them, seeing that it is no longer present? The organism which has been in circuit must yield them itself, and can only yield them *because it has been in the circuit,* since otherwise it would not have done so."

It would, as Pflüger remarks, be hard to find a more correct description of the peculiarities of the opening excitation; and the recent attempts at giving another interpretation of this original theory of the break excitation (by which it depends upon the disappearance of a peculiar state engendered by the current) can only partially be endorsed.

The later observations of Pflüger and others state that: as the closure excitation is caused by the appearance of katelectrotonus (*i.e.* the sum of alterations in the nervous substance produced at the kathode by current), so the opening excitation is the immediate consequence of the disappearance of the anelectrotonic changes. The alterations of excitability which accompany electrotonus, or its disappearance, seem however to authorise a further step in the explanation of these phenomena. It must always be remembered that (as has been repeatedly expressed from other points of view) no sharp dividing-line between increase of excitability and excitation can be predicated. Rise of excitability beyond a certain point may pass directly into excitation, while, on the other hand, a weak persistent latent excitation, which has not produced any visible consequences, may only be expressed in a heightened capacity for response. Both appearance of katelectrotonus and disappearance of anelectrotonus are accompanied by a marked and easily demonstrated increase of excitability, which reaches its greatest intensity at the poles, and in fact discharges an effective excitation there, provided other conditions are favourable. From this point of view the alterations of excitability in nerve as well as in muscle (which are only the partial manifestation of electrotonus) fall into immediate relation with the excitatory phenomena characteristic of the two moments of appearance and disappearance, closure and opening of the current. There is no special alteration of the living matter fundamental to excitation, and distinct in nature from the alterations expressed in rise of excitability, but both together are different manifestations of one and the same change of state which the excitable substance suffers under the influence of

the electrical current, in the one case at the kathode, in the other at the anode.

A law which appears to hold for all excitable substances depends upon the fact that, after prolonged or repeated closure of a battery current, with unaltered position of electrodes and direction of current, the effect of the closure excitation declines more and more, and finally fails altogether. We have already pointed out for muscle that this depends not upon a gradually developing inexcitability of the entire tract traversed by current, but upon a *local* alteration of that point (or points) at which the excitatory process was discharged primarily, and indeed during the entire closure of the current, *i.e.* the physiological kathode. The simplest proof of this is given in the fact that the muscle reacts vigorously on reversing the current, as a rule even more vigorously than before. The same is true of indirect excitation of the muscle from the nerve. Volta, and after him Marianini, came to the conclusion that each direction of current *diminished excitability towards itself, and raised it for the opposite direction.* "For if current is led through a galvanic preparation so that one leg is traversed in the ascending, the other in the descending direction, the twitches will gradually die out in both legs according to the duration of closure of the current. On reversing the current, lively contractions reappear in both muscles." This phenomenon is termed "the Voltaic Alternative" (*supra*). Rosenthal (26) has recently made the facts relating to it the subject of a thorough investigation, the results of which are summed up in the observation, "*Every constant current that traverses a motor nerve for any length of time throws it into a state of increased excitability to the opening of the same, and closure of the opposite, current, of diminished excitability to the closure of the former and opening of the latter.*" Ritter pointed out that the opening tetanus disappeared, and the muscle became relaxed instantaneously, when the battery current was closed in the same direction as before, just as in direct excitation of the muscles the anodic persistent opening contraction is suppressed by closure of the homodromous current. Rosenthal adds that closure of the current in the opposite direction not merely fails to abolish Ritter's tetanus, but even increases it considerably; while opening of the circuit acts like closure of the homodromous current, *i.e.* neutralises the tetanus. An extinguished

opening tetanus may even be reinstated by closure in the opposite direction, if closure and rapid reopening of the homodromous current fail to do so. If the tetanus which derives from the opening of an ascending or descending current is strengthened by closure in the opposite direction, and if this last is persistent, the tetanus which was at first reinforced will disappear gradually. But if the current remains closed after its disappearance, tetanus reappears when it is opened, and the preparation reacts to this current, as previously to its opposite, *i.e.* as if this current had acted from the first upon the nerve. The new current, therefore, in the first instance abolishes the original modification, and then begins to reinstate it.

All these facts find a direct explanation in the polar alterations of excitability, or excitatory and inhibitory phenomena in nerve, as described above, and might indeed have been predicted from this standpoint. In this sense Rosenthal's law is no more than a consequence of the polar law of excitation as set forth above—a necessary effect of the simultaneous and antagonistic changes produced at the two poles by current, and the successive changes at one and the same pole during closure and after opening of the current. It thus appears almost self-explanatory that renewed closure of the homodromous current should at once break off a persistent opening excitation, since at that moment anelectrotonus would again prevail at every point of the nerve at which the excitability had been heightened. Closure of current in the opposite direction would of course have the contrary effect, since excitation resulting from the vanishing anelectrotonus would be supported by the katelectrotonus appearing at the same point.

Seeing the importance which has accrued to the application of the electrical current in practical medicine, the many attempts to determine electrotonic alterations of excitability, and the law of contraction on man, become intelligible. Yet it is *a priori* obvious that the difficulties of investigation are incomparably greater, since the complicated and in part intangible relations of current distribution and conduction render any direct comparison of results with those obtained from the stimulation of isolated nerve difficult, and often quite impossible. Under any circumstances the greatest caution is required in accepting the conclusions obtained from experiments on man.

In the older literature of galvanism there is only one often-quoted communication by Ritter (1802), with reference to alterations of excitability in human nerve under the influence of the electrical current. On dipping both hands into two vessels of water connected with the poles of a strong battery, Ritter found after a certain time (he remained half an hour in connection with the battery) that mobility was perceptibly increased in the arm through which current was ascending, while it was correspondingly diminished in the arm traversed in the descending direction. These modifications continued for a short time after opening the circuit. Pflüger saw in this experiment an entire confirmation of his conclusions from the frog-preparation. If a battery is closed through both arms, "the nerves of the arm are traversed by currents of different density from the brachial plexus, or the spinal cord with its motor-nerve roots, because the cross-section of the path of the current is here so large that current density may, generally speaking, be regarded as minimal. For this reason the arm traversed in a descending direction may be pictured as if the positive electrode was applied to the shoulder, the negative to the hand. That traversed in the descending sense must correspond with the opposite distribution." Now since stimuli above a descending current discharge twitches weaker than the normal, those above an ascending current on the contrary being stronger, the conformity with the laws of electrotonus would seem to be complete, when it is remembered that "the sensorium itself here takes on the business of excitation above, in the one case, the positive, and, in the other, the negative electrode." At a much later period Fick (27) again endeavoured to estimate the electrotonic alterations of excitability in man. He tried to polarise the ulnar nerve at the posterior side of the internal condyle, in order to test the anelectrotonus, but without success. "At an almost unbearable strength of current (10–14 Bunsen) no trace of inhibition was visible in the muscles supplied by the ulnar nerve." Fick ascribed his failure to the impossibility of applying sufficiently strong currents, which is the more improbable, since electrotonic alterations of excitability appear with extremely weak currents.

This was followed by the investigations of Eulenburg (27), Erb (27), Samt (27), and others, which partly confirmed and partly contradicted the conclusions of Pflüger. Eulenburg agreed

with him on the ground of his own experiments, finding invariably a diminution of excitability in the region of the anode, an augmentation in that of the kathode. Erb, on the contrary, observed on his own ulnar nerve an initial decrease of excitability near the kathode, and increase near the anode, which, as was subsequently pointed out by Helmholtz and admitted by Erb, is essentially due to the formation of secondary electrode points produced by relations of conductivity within the arm. Samt again obtained contradictory results in different cases, and referred this apparent inconstancy of reaction to an inconstancy of the nerve itself.

No one who is unprejudiced can doubt (in spite of these contradictions) that if it were possible to test human motor nerves in the same unexceptionable manner as the nerve of a frog's leg, there would be essentially the same reaction of excitability under the influence of a battery current—this effect being only masked in man and other intact animals by the masses of tissue which surround the nerve, and the complications that arise in applying the electrodes. De Watteville (27) in fact finds, with due precaution against every possible source of error, that there is complete conformity between the electrotonic alterations of excitability in the nerves of man and in frogs' nerves, both as regards the effects during closure of the modifying constant current and the after-effects of opening the circuit.

These considerations, which apply more especially to the difficulties and fallacies attending the investigation of electrotonus in man, are no less apparent in all experiments brought forward in proof of the law of contraction on other intact living animals. There is again great uncertainty among the different authors, both as to results and in method. It appears to be quite impossible to speak of any definite *direction* of current in the nerve, as long as it is still *in situ*, since, as Hermann points out, "the current necessarily divides so that it flows through both apparently extrapolar tracts, and that in a direction contrary to the intrapolar current" (H. *Handb.* ii. 1, p. 62, Fig. 187). For this reason it has been usual to fall back upon the so-called "unipolar" (more correctly monopolar) method of stimulation, the application of which is (*supra*) sometimes of value in direct excitation of the muscle, in testing the local visible action of current at the point of greatest density. For nerve, however, it must be regarded as illusory to test, at any

strength of current, the action of a single isolated pole. It is clear that if *one* pole be applied as close to the nerve as possible, while the broad surface of the other rests upon any distant (indifferent) part of the body, the density of the current must be unequal at the physiological anode and kathode of the nerve, but by no means to such an extent that the one pole alone is involved in respect of physiological action. This might occasionally be the case with minimal currents, but with even a low increase of current intensity the action of the other pole must come into play. Every nerve that has an anode must have a kathode also, even if only *one* electrode is directly connected with it, and it depends on the ratio of density between the two poles whether one or the other acts alone or preponderatingly. This agrees with the fact that the make twitch ("anodic closure twitch" of the pathologist) is observed in monopolar excitation of a motor nerve with the anode as well as with the kathode. The widespread opinion among pathologists (*e.g.* Brenner, 27) that the results of monopolar excitation of nerve may, theoretically, be set side by side with the facts of ordinary bipolar excitation, and the recent acceptance of this view by some physiologists (Jofé, 28), cannot be admitted for the study of electrical excitation of nerve, although the monopolar method may legitimately be applied in single cases. The above theory would undoubtedly lead, as in the case of Jofé, to false conclusions,—contradicted by the many facts and experiments underlying the established principles of electro-physiology, which must be the substrate of all future discoveries. We must therefore set aside all attempts to demonstrate the law of contraction in man and in intact animals, since no new points of view can be elicited from them.

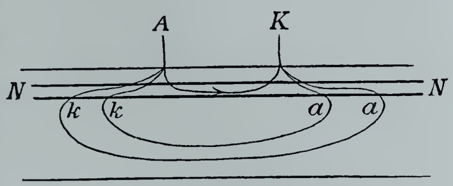


FIG. 187.—Schema of current distribution in a nerve *in situ*; *kk*, virtual kathodes; *aa*, virtual anodes. (Bernstein.)

IV. EXCITING EFFICIENCY OF ELECTRICAL CURRENTS

It is evident that the phenomena underlying Pflüger's law of contraction must be more or less altered by local or general

alterations of excitability in the nerve, so that it is no wonder if, under certain conditions, there are apparent exceptions from the rule. Apart from the well-known tendency of "cooled frogs" to sustained tetanic excitation, which renders them almost entirely unsuitable to the demonstration of the law of contraction, we have to remember the influence exercised by the proximity of an artificial cross-section, not merely upon general excitability, but also upon the mode of action of the battery current.

As regards the former, the raised excitability at the cross-section of a medullated nerve must be regarded essentially as a consequence of katelectrotonus, produced within a certain tract from the cross-section, by internal short-circuiting of the nerve-current,—a fact to which we shall return later. We must first consider the *influence of the transverse section upon the polar action of current.*

If unpolarisable electrodes are applied to the cut end of a motor nerve of a frog, so that the lower electrode in contact with the "long section," and the upper resting on the cross-section, are sufficiently approximated, *the intrapolar tract being very short*, the effect, even with minimal currents, invariably corresponds with the third stage of the law of contraction. At a somewhat greater distance of the peripheral electrode (intrapolar tract = 1–2 cm.) the effect of excitation with weak currents is, on the other hand, a closure twitch with ascending, a closure and an opening twitch with descending direction of current. In this connection we have also the experiment of Heidenhain (29), who divided the nerve between the electrodes and closed up the cut ends again; whereupon, if the incision was made sufficiently near the myopolar electrode, the activity of the latter alone persisted. The zone of depressed excitability in the region of the cut surface in nerve appears to be considerably greater in warm- than in cold-blooded animals. At least the experiment comes off with a greater distance of electrodes in the first case than in the last. If the sciatic nerve of a mammal or bird is exposed in its full extent, and then divided (after previously determining the exclusive effect of *closure* with not excessively strong ascending or descending currents, at the electrode proximal to the centre), there will, with the electrodes close together (about 1 cm.), under the same conditions as before, be a closure twitch only with descending direction of current, an opening twitch with ascending

direction. Similar effects may be observed in frog's nerve on warming the cut end to 40–60° C., or by freezing for an extent of about 1 cm. By gradually moving the electrodes along a distance of 1–2 cm. it is easy to find the place at which, beginning with minimal currents, there is with ascending direction of current a break twitch, with descending direction a make twitch, only. This is obviously another proof of the law of polar excitation.

We have seen that the closure and opening of a current sent through a regular parallel-fibred muscle will only excite normally when the active electrode is at the uninjured end of the muscle. The explanation of this phenomenon as given above leads us to conjecture, from the wide-reaching conformity of reaction to the electrical current in nerve and muscle, that analogous effects would appear in the partially injured nerve also. But we have seen that it is not sufficient to apply one electrode to the cross-section of an otherwise normal nerve, while the other rests upon any point of the longitudinal surface, in order to obtain the effects corresponding with the third stage of Pflüger's law: it is necessary to destroy a considerable portion of the nerve from the transverse section, while as far as possible preserving its finer histological structure. This, as we shall presently see, is due to the fact that there are in medullated nerve (in consequence of a peculiar diffusion of the exciting current on either side of both kathode and anode) innumerable points where the current leaves or enters, so that the "physiological kathode" or anode extends over a comparatively large portion of the nerve, according to the strength of current at the moment. The intrapolar tract of nerve thus falls into two parts, differing according to its length and the intensity of the current, and termed respectively anodic and kathodic, while each of these also embraces a larger or smaller portion of the extrapolar region. These two segments, in one of which (the kathodic) activity is set up simultaneously at many points at closure, in the other at opening of the current, are separated by a spot known as the "indifferent point."

If the nerve is destroyed as locally as possible, without essential alteration of structure at the point corresponding with the electrode distal to the muscle, the *extrapolar* interference from the kathodic or (according to direction of current) anodic section is eliminated; but the excitatory action of the *intrapolar*

portion is in no way abolished, so long as excitability is not materially depressed at the points adjacent to the indifferent point. For these must obviously play the same part in relation to the effectuation or failure of the excitation proceeding from the upper electrode as the fibre-ends in the parallel-fibred muscle traversed by current, and injured at one end (Biedermann, 30).

Certain chemical substances may also be employed for the partial killing of medullated nerve, and Harless (31) has communicated observations on the effect of ammonia upon the nerve-trunk, which agree essentially with the above results from local death of the nerve. Ammonia, when applied in a concentrated solution, destroys the vital properties of the nerve at the point of application without exciting it, or (at least at an early stage) essentially altering its structural relations. Thus by applying ammonia with a little brush (Harless) to points of the intrapolar tract, the kathodic or anodic section of the nerve traversed by current (*i.e.* the sum of all points which at given strength of current and position of electrodes must be regarded as exit- or entry-points of the current) may be functionally cut off, and the intrapolar tract divided at the indifferent point, without alteration of structure; so that in the case before us only those excitatory effects can come into play which correspond with the peripheral electrode, *i.e.* with descending direction of current the closing, with ascending direction the opening excitation. Since the effect of ammonia (and to a lesser degree of other chemical substances in solution) spreads in time with even carefully localised application beyond the original point of contact, becoming weaker in proportion with the distance from the seat of direct action, it is clear that after applying ammonia in the region of the central electrode, the modifications of excitability in successive sections of the nerve must be very gradual. It is consequently unnecessary to apply the ammonia to the intrapolar tract itself; it is sufficient (especially if the electrodes are not too far apart) to apply it to the points of the nerve which lie beneath the central electrode, or even, if the excitation is in the continuity of the nerve, on the far side of this, within the "centropolar" region. When the advancing ammonia-effect has penetrated to the region of the lower electrode, it is of course desirable to shift the electrodes (at their original distance) farther along the nerve. If, however, the electrodes are placed so that the distribu-

tion of current corresponds with the above conditions, the exclusive effect of excitation will be the appearance of the closure twitch with descending direction of current. In regard to the action of weak ascending currents, there is a perceptible difference from the cases of partial death of the nerve as previously described. For while in these last even weak ascending currents (and an arrangement of the electrodes at which the same currents when descending produce only a closure twitch) elicit unmistakable opening twitches hardly less in size than the latter, these fail altogether with local application of ammonia, or appear merely as a trace when the drug begins to act, or with marked strengthening of the current.

When Pflüger formulated his law of contraction in 1859, it seemed hardly doubtful that the effectuation of the opening stimulus in the motor nerve depended in first degree upon the momentary intensity of current. This view was confirmed by the majority of later workers in this department. Yet Ritter, and subsequently Nobili, had already pointed out as a second factor the differing "states of excitability" in the nerve. Rosenthal and v. Bezold (32) accordingly drew up a law of contraction for moribund nerve, which conforms perfectly with Pflüger's law, and by which, with unaltered (low) strength of current at the same point of nerve in three successive stages of dying, the same alternating effects of excitation are observed as appear in fresh nerve (according to Pflüger's law) with weak, medium, and strong currents. These changes may be simply explained on Pflüger's theory from the course of the alterations of excitability, which (according to prevailing views) characterise the single points of nerve that is in process of dying, and which appear at the more central points before the peripheral.

Pflüger in the first instance deduced his law from observations taken almost exclusively from the isolated nerve-muscle preparation of the frog, where the conditions of excitability are not essentially different from the normal. For this preparation, therefore, his law is practically uncontested.

Yet there have been objections even here to its validity in the case in which the excited nerve is still connected with the central organs of the living animal.

Bernard, Schiff, and Valentin (33) all agree that the electrical excitation of undivided nerve "produces contraction of the muscle

at closure only and not at opening of the circuit, whatever the direction of the current," provided only that it is not too strong. Valentin, who characterises this reaction as "the true law of contraction in vigorous, unaltered, living nerve," certainly carried out his experiments under conditions that did not admit of a fair estimate of current distribution, since he introduced (metal) electrodes into the thigh of the intact animal. This, however, matters the less, since Claude Bernard and Schiff had already arrived at the same results on stimulating the exposed nerves (connected with the central organs) of vertebrates, of different classes. Bernard already inclined to the view that the nervous centres exert a special influence upon the efferent nerve-trunks, thus keeping up the normal excitability, and enabling them to fall into excitation at the *entrance* only of (not unduly strong) currents. The following remark seems at all events to bear such an interpretation: "Le nerf moteur tire ainsi ses propriétés de la moelle. Il les perd à l'air; mais il peut les reprendre, pourvu qu'il communique encore avec le centre nerveux." At the same time, the experiment adduced as evidence hardly justifies the conclusion. It is merely that a partially isolated frog's sciatic regains its normal excitability, when the part is moistened, after previous alteration from drying.

The idea that the failure of the opening twitch, on exciting undivided nerves with even strong currents, is due to an inhibitory impulse from the central organ, finds definite exposition in a recent work by T. Rumpf (33). The experiments were mostly carried out on the same preparation as was employed by Bernard. The sciatic nerve forms the only connection between one of the legs and the otherwise intact body of the frog. From the fact that here, "in the nerve connected with the central organ, the opening twitch of the ascending current occurs much later (*i.e.* with stronger currents) than in that separated from the central organ"—as appears still more plainly when the spinal cord is cooled by external application of some freezing mixture,—Rumpf concludes that "constant effects are visible in the motor nerve connected with the central organ (as expressed in alterations of electrical excitability) which cannot be demonstrated in a nerve separated from its centre, since in this case the opening twitch either appears simultaneously with, or shortly after, the closure twitch." The latter is "not modified" by the section.

Hermann (34), finally, points out the possibility "that the opening excitation, which is dependent on the disappearance of some change in the nerve, may be influenced by a certain resistance of the nerve to deeper effects of the current (at an earlier stage of excitability)."

It is remarkable that the different accounts of the initial appearance of the opening excitation, on stimulating with *weak* currents, *i.e.* at the first stage of Pflüger's law of contraction, should again vary in the case of nerve separated from its centre. Pflüger himself lays down that the make twitch is the primary consequence of stimulation with either direction of current, agreeing with the observations of Bernard, Schiff, v. Bezold, and Rosenthal. Heidenhain (18), on the contrary, finds in most cases that the closure twitch with ascending, the opening twitch with descending direction, is the first effect of stimulation with minimal currents. Sometimes, however, he obtained only a closure twitch with both directions of current. Wundt (35) made similar observations.

The perfectly regular effects of excitation, with a given arrangement and distance of electrodes in divided or partially killed nerve, gives rise to the conjecture that the differences cited may perhaps be explained by differences in the position of the electrodes upon a nerve divided from its centre.

We have already seen that in exciting the cut end of a freshly exposed nerve (one electrode being applied to the cross-section itself, or to a point of the nerve close to it) the immediate effect of closure of a minimal descending current is a twitch of the muscle. A slight increase of current elicits a closure twitch with ascending, as well as an opening twitch with descending direction of current. These are approximately equal, and weaker than the descending closure twitch at the same strength of current. The ascending opening twitch only makes its appearance with much greater strength of current. The effects of stimulation are very different, under otherwise uniform conditions, with weak and even with medium currents, if both electrodes are applied to a section of the same nerve lying a little deeper. For then, without exception, *only the closure twitch occurs with both directions of current,* as was pointed out by Rosenthal and v. Bezold.

The electrodes may be shifted to the immediate vicinity of the muscle, or middle portions of the nerve may be excited; so long as the most central contact is sufficiently distant (about 1 cm.)

from the cross-section, the described reaction undergoes no change, or such only that the closure twitches discharged at different points of the nerve, with uniform distance of electrodes and strength of current, are of different magnitudes—corresponding with the fact that the excitability of a divided nerve is, as a rule, not merely greater in the vicinity of the cross-section than at the periphery, but also that certain special points in its continuity are characterised by a higher excitability.

If with descending direction of current the central electrode is placed quite close to the cross-section, there is invariably an opening twitch along with the closure twitch, at any given position of the other electrode, and that at very low intensity of the exciting current, hardly exceeding the threshold of activity. With ascending direction of current, on the other hand, the peripheral electrode must be brought to within a few millimetres of the kathode at the cross-section, in order to demonstrate the opening twitch, as well as that at closure. The closure twitch is then, with low intensity of current, very small, and often entirely absent; the same applies, after reversing the current, to the opening twitch.

The dependence of the opening excitation upon the proximity of the cross-section of a nerve to the anode stands out with especial clearness when (as was first shown by Heidenhain, 29) the electrodes are applied anywhere along the continuity of a nerve, and the "centropolar" tract so shortened by amputation that the cross-section is brought into the immediate vicinity of the upper electrode. The opening twitch is at first seen only with descending direction of current, and it is not till the intrapolar region is shortened, whether by bringing the lower electrode close to the upper, or, as was said before, by making the cross-section within the intrapolar tract itself, and applying the cut ends together again, that the opening twitch appears with ascending direction also, while the closure twitch becomes less, or fails altogether.

The most obvious interpretation of the efficacy of even very weak opening stimuli in the immediate proximity of the cross-section of a nerve is that derived from the well-known observations of Heidenhain (29), to the effect that on applying a cross-section either to a fresh nerve or to one in which excitability is already declining, the response of each point not unduly remote

is considerably increased towards the electrical stimulus. This is caused by the fact that both ascending and descending currents, which produce only minimal effects of excitation upon closure, will, when led in by unpolarisable electrodes to the lower portion of the nerve, produce almost maximal closure twitches, provided the nerve is divided at not too great a distance from the central electrode. The appearance of the break twitch seems, at first sight, to indicate the same thing, since it is hardly perceptible with low intensity of current, if the anode falls within the region which is obviously the most strongly affected by the cross-section.

Although it is indisputable that the opening excitation takes effect at a very low intensity of current if the anode is placed in the immediate vicinity of a section (mechanical, chemical, or thermal) applied to the nerve, the preceding, and till now generally accepted, interpretation ought not to pass muster. We need not dwell on the fact (as frequently confirmed by experiment) that the opening twitch, in those very nerve-muscle preparations which are taken from animals brought fresh from a cold chamber into the laboratory, and in which excitability is very high, appears plainly for the first time with relatively strong currents, while in preparations from less excitable frogs there is sometimes (if rarely) an opening excitation without the application of any transverse section, at a low strength of current—because the inevitable closure tetanus masks the weaker opening effects, which are thus detected only by a delay in the muscular relaxation.

On the other hand, decisive evidence against the exclusive agency of rise of excitability in the production of the opening twitch is afforded by the fact that division of a nerve in the vicinity of the anode is at once followed by the appearance of the opening twitch; even when excitability has from any reason been much reduced during the experiment, so that (as far as can be judged from the height of the closure twitches then discharged) it is not, even near a fresh cross-section, as great as it was at the same point in the uninjured nerve. Nevertheless the opening twitch fails completely with the same strength of current at the commencement of the experiment, while it appears immediately after making the cross-section, in spite of the absolutely lower excitability.

In this connection there are certain very instructive experi-

ments on nerve, relating to preparations enclosed for several hours in a moist chamber at the temperature of the room; excitability being in consequence much diminished. Immediately after dividing such a nerve near the electrode distal to the muscle, a weak descending current will discharge a break twitch, along with the make twitches, which are not essentially altered in magnitude by the incision. The ascending closure twitch may indeed appear rather larger than before, but is nothing like its original height. It thus appears that other factors come into play near a point of section, which favour the appearance of the opening twitch independently of augmentation of excitability.

At this point we must ask whether the opening excitation of the nerve is conditioned to the same extent as the closing excitation by its state of excitability at the moment. Whether, in other words, it is possible to produce opening twitches with weak currents, by artificially increasing the excitability to closure stimuli.

This question might seem to be already decided by the experiments of Rosenthal and v. Bezold (32) to which we have frequently alluded, since in these observations the opening twitch appears even with weak currents, owing to the alleged rise of excitability during the spontaneous dying of the nerve. But this appears to occur only under certain conditions. At all events, Biedermann has been unable, on repeating the experiment, to discover the regular succession of the three stages of the so-called law of contraction in moribund nerve, on exciting any point with uniformly weak currents—provided the preparation was enclosed in a moist chamber, and carefully preserved from injury, and especially from evaporation. As was pointed out above, even the primary stage of increased excitability described by Rosenthal in the moribund nerve was not apparent under these circumstances; there was rather for the most part a gradual sinking of excitability. It should also be noted that, with unaltered position of electrodes, the closure of the ascending current is first to become ineffective, so that at a certain stage of dying the descending closure twitch is the sole effect of weak currents. This fact agrees with the so-called Ritter-Valli law, by which excitability is more quickly extinguished at points nearer the centre than at the periphery. It would seem, however, as already pointed out, that the facts which support this

law relate not so much to unequal diminution of excitability at different points of the nerve, as to impaired conductivity.

On the other hand, it is a well-known and easily confirmed fact that the response of a nerve to weak electrical stimuli is considerably heightened by loss of water; and that indeed—as was pointed out more especially by Harless and Birkner (36)—at a time when the spontaneous twitches which induce the so-called desiccation-tetanus are still completely absent. Grünhagen and Mommsen (36) have recently shown that "a nerve is the more sensitive to the effect of the electrical current in proportion with its loss of water, especially when the characteristic spontaneous twitches make their appearance." Hence it is of interest to see whether the opening of a battery current of low intensity acts in this case as sufficient stimulus. Harless discovered that after partial loss of water in the nerve, the opening twitch was discharged by weak ascending, as well as descending, currents, and it is easy to confirm the truth of this fact by the simple experiment of exposing a frog's nerve, laid over unpolarisable electrodes at not too high (room) temperature, to gradual evaporation, and exciting it from time to time with ascending or descending currents, the intervals not being excessive. It is advisable in these experiments to use a nerve-muscle preparation still connected with the spinal cord,[1] in order completely to exclude the action of the cross-section, although precisely the same results are obtained on exciting the peripheral tracts of divided nerves. Moreover, in the last case the preparations with divided nerves may be left for several hours (Mommsen's process) in 0·6 % NaCl, in order to equalise the alterations of excitability caused by section.

V. Closing and Opening Tetanus through Electrical Excitation

1. *Conditions of Production by Excitation of Frog's Nerve*

The first effect of commencing desiccation appears in the graphic record of the muscle-contraction, as a more or less

[1] Allusion to a nerve still connected with its centre always implies a preparation taken from a chloralised frog, consisting of the isolated vertebral column (after destroying the brain), sciatic nerve, and corresponding gastrocnemius muscle, on the same side.

considerable augmentation in the height of the closure twitches. At a later stage the closure of even weak currents causes tetanic shortening of the muscle. The opening twitch then appears along with the closing contraction. The direction in which this first occurs depends less upon direction of current than upon what point of the tract of nerve between the two electrodes is submitted first, and in a higher degree, to the influence of dehydration. If the electrodes are applied to an undivided nerve, so that the sacral plexus falls for the greater part within the region of the upper electrode, the opening excitation will be seen, on account of the slow drying of this the thickest portion of the nerve, to appear first with ascending direction of current; while, if the electrodes are placed in the middle of the nerve, the break twitch follows almost simultaneously upon the strengthened make twitch, with both directions of current, unless one or the other part of the nerve is protected from loss of water by frequent moistening with 0·6 % NaCl. If the excitation is limited to weak currents, the closure lasting only so long as to produce a visible opening excitation (a few seconds is, as a rule, sufficient), there will regularly be a more or less delayed appearance of the opening twitch, the magnitude of which depends to a high degree upon the duration of closure of the current. If this is very brief, the break twitch may fail altogether, even when the excitability of the nerve is considerably increased, while a vigorous twitch never fails to appear when the current remains closed a little longer. It is remarkable that the form of the curve also depends essentially upon the duration of current, every transition existing between a simple muscular contraction, which cannot be distinguished from the closure twitch, and a long-sustained tetanic shortening (Ritter's opening tetanus).

That this opening tetanus, which readily appears at an advanced stage of desiccation, after a brief closure of weak currents, must be regarded as homologous with the opening twitch of earlier stages, inasmuch as both are due to the same causes (to be described below), is evident both from the presence of the above-described transitional forms, and from the fact that the opening tetanus makes the same retarded entrance as the opening twitch.

Pflüger (2, p. 75) was the first to draw attention to this significant fact in relation to the opening twitch. He observed

repeatedly, on stimulating the deeper portions of the sciatic of *Rana esculenta* with weak descending currents, that "the opening twitch responded to the moment of opening the descending current at a very long interval, often lasting for several seconds."

Such a striking delay has been observed by Biedermann in rare cases only, and never on nerves in which excitability had been raised by loss of water; and notwithstanding the comparatively small number of experiments, and the possibility of individual variations, it is impossible not to suspect that Pflüger had before him in these cases preparations which were in the first stage of desiccation. We have never observed the phenomena in question, save when the excitability of the nerve was artificially raised above the normal by certain influences to be described below. Eckhardt (37), *e.g.*, explained the excitatory manifestations observed with the action of neutral salts of alkalies (more especially NaCl, as a solid, or in strong solutions), as caused by abstraction of water—comparing them directly with the excitatory phenomena concomitant with the drying of the nerve. And there is in fact a great similarity of action in both cases—as regards alterations of excitability in general, and also the appearance and character of the opening excitation.

The use of concentrated solution of NaCl is so far advantageous that it is more easy to localise the effect to a definite tract of nerve therewith, than in desiccation; but, on the other hand, there is the objection that in electrical excitation of a nerve-section treated with NaCl the tendency to tetanic contraction of the muscle is far more pronounced with even the weakest closure or opening stimuli than it is in desiccation, so that this method nearly always results in opening tetanus, and rarely in opening twitches.

Since in treating a nerve with NaCl in its entire length the closure tetanus (which at once appears, independently of direction of current, provided that, as always, weak currents are employed) would considerably interfere with the recognition of excitatory phenomena at break of the current, it is well to confine the action of the NaCl as far as possible to the region of the anode.

It is convenient in these experiments to employ the form of unpolarisable tube electrode first described by Engelmann (38). A little pad of cotton wool soaked in saline is then placed upon one of the electrodes, so that a length

of nerve, the breadth of the glass tube, is covered by it. It is advisable to bring the whole preparation, with the electrodes, into a moist chamber, to preserve the free end of the nerve from drying in prolonged experiments. The muscle is connected with a writing-point outside the chamber by means of a thread wound round a cylinder, by which the changes of form are recorded on the cylinder of a kymograph rotating at varying rapidity. On exciting with weak currents a plain increase of effect from closure will be observed after a few minutes, if the current leaves at a part of the nerve treated with NaCl. The twitches, however, soon become tetanic, and after a short time there is a marked

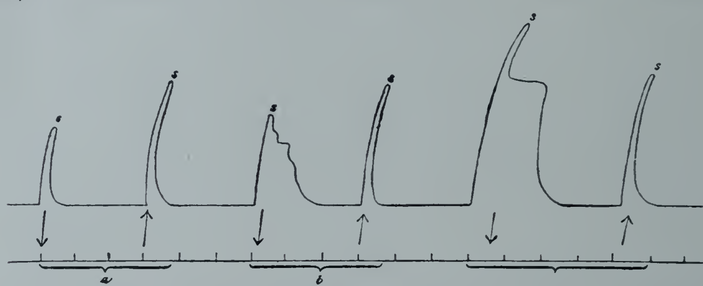


FIG. 188.—Effect upon excitability, of local treatment with salt at the kathode. Transition from descending closure twitch to closure tetanus.

tetanus (Fig. 188) at every closure of the current in the direction indicated, which at first disappears again completely on opening the circuit, but is persistent at later stages of the NaCl effect, when of course further observations are impossible. At a time when, after application of NaCl to the electrode proximal to the muscle, a weak descending current already discharges a vigorous closure tetanus, the closure of the same current in the opposite direction yields, as a rule, only a simple twitch, which cannot in time-relations or magnitude be distinguished from the closure twitches discharged under the same experimental conditions by local application of NaCl. This fact is by no means without interest, since it shows that, as regards the magnitude of final result from the excitation of any point of the nerve, it is a matter of indifference whether the "excitatory wave" discharged passes through a tract of nerve already in a condition of heightened excitability, or no.

The opening of weak ascending currents has, as a rule, no effect after local application of NaCl at the anode, although on

reversing the current the closure produces a vigorous tetanus. It is necessary either to strengthen the ascending current, or to prolong the closure in the same proportion, in order to obtain effective (usually tetanic) opening excitation. Neither of these is required at a later stage of local salt treatment. The muscle then becomes disturbed very quickly, and goes into the familiar salt tetanus, which makes further experiment impossible, unless the affected part of the nerve is washed with 0·5 % NaCl (after taking away the pad), when it returns to the state in which it shows increased excitability without discharging any spontaneous excitatory phenomena.

In other respects the character of the opening effects after

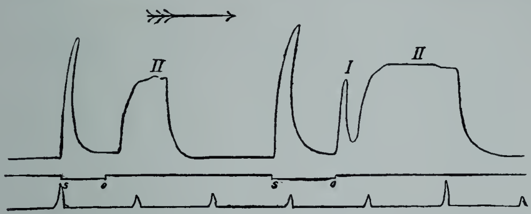


FIG. 189.—Frog's nerve-muscle preparation. Stimulation in the middle of the strip of nerve. Ascending current. After applying a pad of cotton wool soaked in concentrated NaCl to the anode for three minutes, opening of a weak battery current produces tetanus after a brief closure, which makes a delayed entrance (II). After single closure of a stronger current, the opening twitch (I) appears between the moment of opening a current of equal intensity with the former, and the commencement of tetanus.

treatment with NaCl corresponds almost completely with the analogous phenomena described above for drying nerve; the delayed entrance of the break contraction, and its dependence upon the duration of closure, being in most cases very obvious (Fig. 189). It is therefore unnecessary to go into further details in respect of these curves, and we may pass on to the interesting effects of treatment with very dilute alcohol.

Mommsen (*supra*) showed that the excitability of motor nerves was considerably increased by the application of a weakly alcoholised (1–2 vols. %) NaCl solution, the augmentation only giving way after prolonged treatment to diminution, and subsequent inexcitability. Even then it is possible to restore excitability by washing with 0·6 % NaCl.

When the sciatic of a frog's nerve-muscle preparation is treated in its entire length with alcoholic saline, and excited every minute with a weak ascending or descending battery current, the

first effect is invariably a considerable increase in height of the closure twitches, without actual tetanus. Almost at the same time (usually after 2–4 minutes) a twitch, which is usually delayed, appears with the opening of the current also, provided the duration of closure is not too brief (Fig. 190).

The duration of closure required, under the given conditions, to produce an excitation on opening the circuit, depends of course, apart from its intensity, upon the degree of alcohol effect, *i.e.* strength of solution and length of application. The rise of excitability in the nerve usually occurs fairly soon, when it is treated with not excessively weak alcoholic saline, and the break twitch

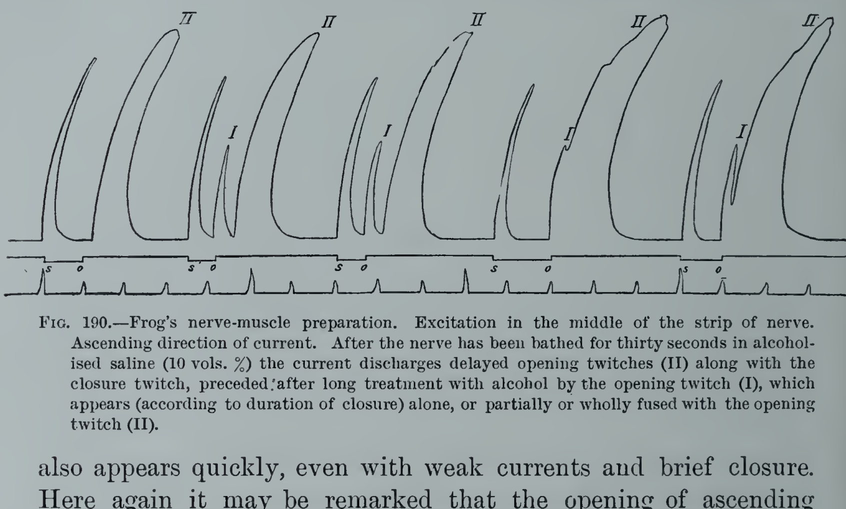


FIG. 190.—Frog's nerve-muscle preparation. Excitation in the middle of the strip of nerve. Ascending direction of current. After the nerve has been bathed for thirty seconds in alcoholised saline (10 vols. %) the current discharges delayed opening twitches (II) along with the closure twitch, preceded after long treatment with alcohol by the opening twitch (I), which appears (according to duration of closure) alone, or partially or wholly fused with the opening twitch (II).

also appears quickly, even with weak currents and brief closure. Here again it may be remarked that the opening of ascending currents excites, as a rule, a little sooner than descending currents —which is no doubt related to the appearance of the so-called "negative modification" of katelectrotonus in the last case.

The alcoholised nerve never sets up spontaneous tetanus, and isolated twitches of the muscle only appear occasionally with strongly alcoholised saline—up to 20 vols. % (Mommsen)—so that the dependence of the opening excitation upon the state of excitability of the nerve, as well as upon its special characteristics, may be studied here as in no other case—the raised excitability remaining for a long time constant.

Two characteristics of the break excitation as it appears with artificially raised excitability of a nerve in consequence of weak battery currents are, as we have noted (*a*), the more or

less pronounced but always perceptible delay in the entrance of the twitch; (*b*) the dependence of the magnitude and form of the curve of the twitch upon duration of closure. Both are clearly seen in the graphic tracing of the opening twitch, as discharged with weak currents from the alcoholised nerve.

The extent of the delay varies within a considerable range. At times it is hardly perceptible; in other cases the shortening of the muscle is much retarded. The determining factors are here duration and intensity of current—the "latent period" being usually reduced as these increase.

The "latent period of the opening excitation" is also affected, in alcoholised nerve, by the degree of increase of

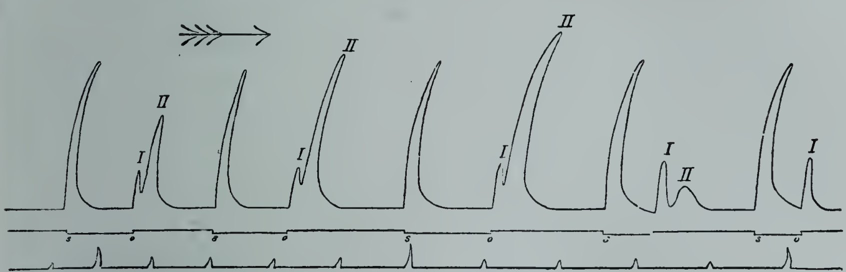


FIG. 191.—Alcohol treatment of nerve. Method of experiment as in Fig. 190. Effect of duration of closure upon height of break twitch (II). Break twitch (I) appears quite independent of the same.

excitability, so that it usually appears much greater at the beginning of a series of experiments than during their course, even if in this case the influence of the single stimuli following at short pauses (with constant duration of closure) is of more importance. As Pflüger pointed out, "the phenomenon (of delay) alters after repeated closures, since the break twitch follows more and more closely upon opening, until finally no perceptible interval remains."

A glance at the opening twitches marked II in Fig. 191 shows the striking dependence of the break excitation upon duration of exciting current under the given conditions of experiment—comparatively slight modifications of current sufficing, on the one hand, to suppress the twitches altogether, on the other to discharge maximal contractions. So far the effect of electrical stimulation upon alcoholised nerve, and upon nerves of which the excitability has been heightened by partial loss of

water, or treatment with NaCl, correspond almost exactly. Yet the main features of the curve of contraction (Fig. 192, II) differ —albeit inessentially. In the drying nerve the discharge of simple opening twitches (at a certain stage which immediately precedes the appearance of spontaneous excitatory effects) fails even with very weak currents, so that there is only tetanic contraction of the muscle (*Ritter's opening tetanus*) as appears in an even higher degree in nerves treated with NaCl; the alcoholised nerve, on the other hand, requires a tolerably protracted passage of current, along with moderate intensity of stimulation, to produce a definite opening tetanus. At most there will only be extended twitches—even with prolonged closure,—which

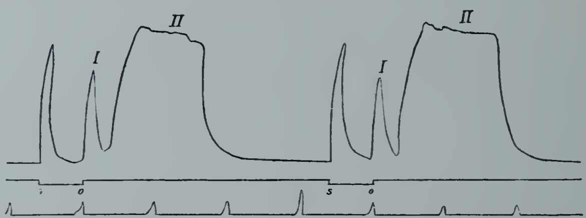


FIG. 192.—Frog's nerve-muscle preparation. Ascending direction of current, otherwise the same experimental conditions as in the previous Figs. Effect of commencing desiccation on the result of breaking a battery current of medium strength. The opening twitch (I) appears as the initial phase of the delayed opening tetanus (II).

must be regarded as transitional forms between the simple opening twitch and persistent tetanic shortening of the muscle.

This agrees with the fact that the appearance of closure tetanus in weak electrical excitation of alcoholised nerve must be regarded as exceptional, although the curves of both closing and opening twitches are distinguished by their rounded tops from such as are obtained on exciting normal nerve by instantaneous stimuli (single induction shocks), or by the closure of a battery current.

These experiments show conclusively that while in normal, uninjured nerve it is never possible to obtain an opening excitation from weak currents, this may result when excitability is artificially raised: thus seeming to justify the view that the appearance of the break twitch on applying a cross-section to the nerve is due to the consequent rise of excitability.

Yet (in addition to the objections already cited) the bare comparison of the opening effects of excitation in the two cases

proves, not merely that there is no correspondence of fundamental characteristics (as would necessarily occur if the same cause underlay the opening excitation in both instances), but that —as becomes more and more evident on investigating the phenomena—there are here two perfectly different effects of current, distinct not merely in regard to appearance, but also in their mode of expression in the muscle.

The characteristics of the opening twitch discharged by the action of weak currents, upon nerves of which the excitability is considerably heightened, are, in first degree (according to the above experiments), its delayed entrance, as also its dependence upon duration of closure; and these distinguish it fundamentally from the opening twitches which appear (under otherwise uniform conditions of experiment) at the transverse section of an otherwise normal nerve. In the curve of the latter there is never, unless finer methods of time-measurement are resorted to, any perceptible interval between the moment of opening the current and the commencement of muscular contraction; the curve is also much steeper, and invariably exhibits a pointed apex, while it never reaches the height of the opening twitches discharged in consequence of artificially raised excitability in the nerve. It is, however, remarkable that the duration of the exciting current affects the *magnitude* only within a very narrow range, and in no case the *character*, of the opening twitches from the transverse section; for the curve of the latter never acquires a more extended form, or becomes tetanic, even when a tolerably strong current traverses the cut end of a nerve protected from evaporation for a considerable time, in the descending direction. These facts alone would justify the assumption of a double opening excitation, distinct in origin and in mode of manifestation; there are, however, further and still more convincing proofs.

In the first place, the uninjured nerve may, under certain conditions, with even weak currents, exhibit opening twitches of precisely the same character as those deriving from the transverse section—independent of action from any incision. Here, however, it is not so much a raised as a considerably diminished excitability of the nerve which seems to favour their appearance.

If the sciatic nerve of a frog is treated, as described, with a moderately strong solution of alcoholic saline (about 10 vols. %), and excited once a minute by an ascending or descending battery

current of low intensity (the ascending direction is, on the whole, to be recommended, because the anodic effect is there developed without interference)—there will soon be seen along with the retarded opening twitch, which is alone visible at first, a second, which commences at the moment of breaking the circuit, filling up the interval before the delayed muscle twitch begins, and thus being in some sort introductory to it (Figs. 190, 191, I). Whether this effect appears as a perfectly distinct twitch, the muscle relaxing again completely before the retarded twitch (opening twitch II) begins, or whether it fuses with the latter partially or completely, depends of course upon the time that elapses between the moment of opening and the commencement of break twitch II, and thus upon the duration of the current also.

The excitability of the nerve sinks gradually as the alcohol

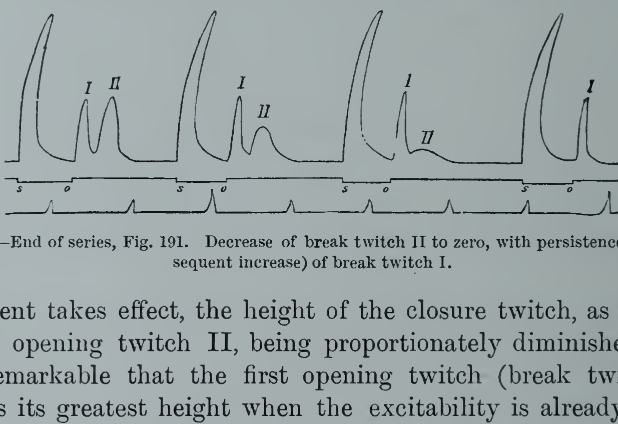


FIG. 193.—End of series, Fig. 191. Decrease of break twitch II to zero, with persistence (and subsequent increase) of break twitch I.

treatment takes effect, the height of the closure twitch, as well as of the opening twitch II, being proportionately diminished, and it is remarkable that the first opening twitch (break twitch I) reaches its greatest height when the excitability is already much diminished. The second opening twitch fails altogether at a somewhat later period, and does not reappear even with prolonged passage of current; break twitch I, however, persists along with the reduced closure twitch, with which it is for the most part equal, if it does not exceed it (Fig. 193). If the whole preparation is freely moistened at this time with a 0·6 % solution of NaCl, it is easy to restore the normal relations of excitability in the nerve, so that a closure twitch is the only effect of excitation at any point, with moderately strong ascending or descending currents. Upon renewed application of dilute alcohol the former series of effects may be repeated a second and sometimes even a third time.

The treatment of a nerve with alcoholic saline has the advan-

tage of enabling us—without otherwise altering the experimental conditions—to follow exactly, on one preparation, the nature and course of the gradual changes developed at break of the current during the chemical action. We thus learn directly that the two forms of twitch may exist simultaneously, and must, therefore, be regarded as distinct effects of current. This cannot be determined with equal certainty from the opening effects of excitation in drying or in "salt" nerves, since the prompt appearance of spontaneous tetanus prevents any prolonged observations; nor would those cases be decisive in which break twitch I alone makes its appearance, since the initial increase of excitability is either wanting altogether, or finds insufficient expression.

Ranke (39) states that "the excitability of the nerve is in the first instance raised by the action of potash salts. It is only later, and with very strong potash, that excitability is depressed, and the nerve dies." He reckons neutral salts of potash among the "fatigue products" of the nerve, giving as characteristic of "nerve fatigue" that "it presents two different stages: the primary stage is a heightening, the secondary a depression of excitability," passing finally into the death of the nerve. The order of alterations of excitability in the different stages of potash effect is therefore the same as in treatment with alcoholised saline; and a similar reaction towards weak opening stimuli might be expected. Experimentally, however, these anticipations are only partially realised.

If the nerve of a nerve-muscle preparation, separated from the central organ, is thoroughly bathed in a very dilute solution (1 %) of KNO_3, a highly characteristic alteration in the reaction from the muscle to excitation of the nerve by weak battery currents will shortly (5–10 minutes) be observed. An opening twitch (of the character of break twitch I) now appears not merely, as before, with the descending direction of current only, so soon as the anode is applied to the cross-section—but is discharged, independently of position and distance of electrodes, with both descending and ascending direction of exciting current, without any apparent increase of response to closure stimuli. In most cases indeed the height of the closure twitches is less than at the beginning of the potash treatment. The same results appear with undivided nerves, still in connection with the spinal cord, and treated with 1 % KNO_3 solution (Fig. 194).

If different points of the nerve are excited from time to time with constant distance of electrodes (about 1–2 cm.) by weak currents, it is usually found that the opening stimulus acts sooner in the part of the nerve corresponding with the plexus, than in deeper parts. It is evident that the saline will take effect more quickly at points where the bulk of fibres in the nerve are still distributed into single bundles, than at a lower part where they are joined into a single trunk, and this—along with the greater sensibility of central tracts of the nerve to injuries (Efron, Clara Halperson)—explains the above reaction. If only the part of the nerve below the plexus is treated with KNO_3 near the lower point of bifurcation, by placing it between two pads soaked in

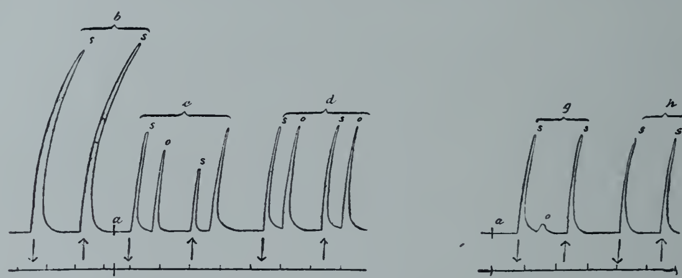


Fig. 194.—Frog's nerve-muscle preparation. A weak ascending or descending current only discharges a closure twitch (*b*) with any position of electrodes. After 5 min. bath of 1 % KNO_3, the excitability of the nerve is lowered. The same current now discharges opening twitches of equal height with the closure twitches (*c*, *d*) from all points of the altered tract of nerve. After washing with physiological saline (15 min.) the opening twitch disappears again (*g*, *h*).

saline, the same strength of current will produce uniform break twitches at all points of that part of the nerve. But if in such a preparation the electrodes are laid closely together upon the plexus, there will either be a closure twitch alone, with both directions of current, if the connection with the spinal cord is still intact, or else, from the proximity of the cross-section, there will be closing and opening twitches, with descending direction of current.

If the action of the potash saltpetre does not affect the immediate proximity of the muscle, but is arrested at about 2 cm. off it, it may be demonstrated that by gradually shifting the electrodes at uniform distance (1 cm.) from the centre to the periphery, the break twitch becomes less and less as the normal portion of the nerve is approached, and an increasing part of it included under the anode—and finally disappears altogether—

while the height of the closure twitch is unaltered, or even increases perceptibly. The same occurs with descending currents, only in this case the electrodes must be brought nearer the muscle in order to abolish the opening twitch, since here the kathode first, and only later the anode, falls within the normal region. The height of the closure twitch then increases conspicuously, showing once more that excitability to closure stimuli is more vigorous at normal points of the nerve than at those which are altered by the action of the potash—although opening twitches are not discharged in the normal nerve, and never fail to appear in the other.

If, at a not too advanced stage of KNO_3 action, the nerve—while giving approximately equal make and break twitches at all points when excited with weak constant currents—is moistened sufficiently with 0·6 % NaCl, it soon appears that while the make twitches are at first unaltered, the height of the break twitches decreases more and more the longer the bath is continued. Finally, after 10–15 minutes, they disappear altogether, with uniform or even much stronger currents, leaving the closure twitch, as at the beginning of the experiment, the sole effect of excitation in either direction (Fig. 194, *g*, *h*).

It was stated above that the break twitches discharged by weak currents in consequence of potash treatment are identical in character with those observed under the action of alcohol to precede the delayed break twitch II, which at first makes a solitary appearance. Twitches analogous to these latter are altogether wanting in "potash nerves."

It is *a priori* not improbable that treatment of a more restricted area with KNO_3 might locally induce the conditions favourable to the appearance of "primary opening twitches" (break twitch I), thus enabling weak ascending or descending currents, with given position of electrodes, to produce an effective opening excitation.

If the same method be employed as in the above-described local treatment of nerve with concentrated saline, currents of low intensity being used for excitation, a different reaction follows in the nerve according as (after applying a pad of cotton-wool soaked in 1 % KNO_3 to one or the other electrode) the solution of potash acts upon the electrode proximal to the muscle or to the centre. In both cases the size of the make twitch during

the first minutes remains unaltered, as can easily be seen from its graphic record. Later on, there is nearly always a difference in the height of the make twitch, according as the current is ascending or descending, and always in favour of that direction of current with which the kathode is at the normal point of the nerve. Sometimes, however, after local treatment of the nerve for ten minutes or more with a 1 % solution of KNO_3, the excitability to closure stimuli of the point affected is hardly diminished perceptibly. On the other hand, there is invariably during this period a much increased susceptibility in the part of the nerve treated with KNO_3 to opening stimuli, however weak, whether the nerve be separated from the central organ or still connected with it.

According as the cotton-wool pad on the electrode is proximal or distal to the muscle, the opening twitch appears, with either ascending or descending direction of current, in addition to the already existing closure twitch, and usually reaches the same magnitude.

Obviously these local alterations of excitability in nerve to opening stimuli also, may be neutralised by washing out with 0·6 % saline.

"Primary opening twitches" do not appear merely in consequence of certain artificial, chemical alterations in the substance of the nerve, which may imply a considerable depression of excitability, and are notably produced by the action of potassium salts: the same alterations are apparently brought about by the electrical current, at its points of entrance into the nerve.

The dictum that electrical excitation of normal and uninjured nerve gives rise to closure twitches alone, independent of direction of current, applies, as we have said, in general to weak and medium currents only. Biedermann has almost without exception obtained effective break excitation with a Daniell cell, after introducing resistance from a du Bois' rheochord, both before and after separation from the central organ (in the latter case at a point of nerve sufficiently removed from the cross-section).

Then, however, we are met by the remarkable fact that immediately after the expiration of an opening twitch discharged by a strong current, the fall of other weaker currents, that had previously acted at closure only, will produce excita-

tion, and that in almost the same degree as the opening of the strong current. This effect, however, soon diminishes, and disappears completely after a few minutes if the nerve is sufficiently vigorous. With otherwise uniform conditions this characteristic after-effect is the more persistent, in proportion with the previous passage of the strong current, and defective vitality in the nerve.

Any point along the nerve may thus (as in local treatment with potash) be rendered sensible to weak and, under normal conditions, non-effective opening stimuli, by making it for a short time the entrance point of a stronger constant current. And as in the previous case the raised disposition to the opening excitation may be neutralised by washing off the toxic substance with an indifferent fluid, so in the excised nerve the continuous process of restitution suffices to neutralise the anodic alterations produced by the current, and to restore the normal insensibility to opening stimuli.

The break excitation which may be discharged at the anodic points of the nerves after brief closure of a stronger current, by currents of lower intensity, is always expressed, as we have seen, in twitches of the muscle, which correspond throughout with those that appear on treatment with potash salts, or in the immediate proximity of a fresh transverse section. This, apart from the absence of any perceptible interval between the break of the current and the beginning of contraction, is more particularly expressed in the uniformity between the curves of the two twitches, and in the slight effect of intensity and duration of exciting current upon the magnitude of the twitches.

A further proof of the correspondence between the break twitches discharged after treating a nerve with potassium salts (these again being identical with the "primary opening twitches" of the alcohol effect), and those discharged by strong currents in normal, uninjured nerve, appears in the fact that the latter are discharged simultaneously with "secondary" delayed opening twitches (break twitch II) in the same preparation. Since Ritter's tetanus is equivalent with break twitch II (*supra*), and since this is sometimes delayed (as pointed out by Wundt), the effect of the opening excitation in such cases either consists in a completely or incompletely separated double twitch, or else break twitch I is introductory to Ritter's tetanus (Figs. 189, 192).

The curves in question were obtained by closing a strong current for some seconds (after heightening the excitability of the nerve in a marked degree by abstraction of water, treatment with saline, or alcohol, which set up a tendency to secondary opening excitation), to predispose the anodic points of fibres for the discharge of primary opening twitches (by currents of lower intensity). So long as the after-effect of the single closure of a strong current persists, the double excitatory action may be seen with the opening of the weaker currents, being indeed very distinct, while with stronger currents the two twitches readily fuse into one, on account of the shortened "latent-period" of break twitch II—as is also the case in Ritter's tetanus. This last fact explains how it has been possible till now to overlook the existence of two quite distinct opening effects of current.

We are here met by the further question, whether the two effects of the break excitation (as disclosed under certain experimental conditions) may, notwithstanding their dissimilarity, be referred to a common origin; or if not, from what cause they are derived.

As regards the first point, a fair and unprejudiced consideration of the facts ought to convince us of the improbability of a single origin for excitatory effects, as unlike in conditions of appearance and general characteristics as the break twitches I and II. While the appearance of the latter seems to imply a considerable rise of excitability in the nerve, the former, on the contrary, enters with depressed excitability; and while with weaker currents there is, as a rule, delayed entrance of break twitch II and of the equivalent Ritter's tetanus (dependence upon duration of current being also very evident), there is never any perceptible interval between the moment of opening and the appearance of break twitch I; moreover, when the conditions of its entrance are once present, the latter is almost independent of the duration and intensity of the exciting current.

The undoubted equivalence of break twitch II and Ritter's tetanus points to a common origin. Pflüger, who regarded every opening twitch as a consequence of excitation of the nerve, by the disappearance of anelectrotonus, gave the same explanation of Ritter's tetanus, and actually demonstrated, by the well-known experiment of cutting off a previously anelectrotonised portion of the nerve, that the opening tetanus originates at that

part. According to Engelmann (4, p. 411), however, it arises here from pre-existing spontaneous stimuli, which were at first inadequate, and now become effective from the positive modification in excitability at the previously anelectrotonic tract of the nerve, on opening the current—thus producing a change of form in the muscle. Engelmann makes special reference to the fact (as is easily confirmed) that "a simple twitch, which cannot be distinguished from the closure twitch, or the twitch from a single induction-shock, appears in fresh nerve-muscle preparations of normal frogs (when preserved from evaporation) on breaking the current." "On the other hand, the opening tetanus (as also the analogous closure tetanus) makes its appearance with the greatest regularity in cooled preparations," the nerves of which are characterised by peculiar excitability—referred by Engelmann to the presence of internal stimuli, that are often so powerful as to induce spontaneous twitches, or even tetanus, when every precaution is taken against evaporation. Further support of Engelmann's views, as to the nature of Ritter's tetanus, is found in an experiment of Grünhagen (40), which shows that "weak tetanising excitation that produced no visible effect before the closure of the polarising current, calls out an unmistakable tetanus when the latter is opened, lasting the longer in proportion with the strength of the polarising current and susceptibility of the nerve." Grünhagen hence deduces the following proposition: "The raised excitability of the nerve at the previously anelectrotonised region, summating with the increased disintegration stimuli, normal to the nerve, results in the opening tetanus of constant currents. These chemical stimuli may be counterfeited by a sub-liminal tetanising excitation."

We should thus expect the secondary opening twitch only when the nerve is, so to speak, in a state of latent excitation. And the above facts relating to the appearance of break twitch II are in complete agreement with this anticipation. For with loss of water from evaporation, or in treatment with concentrated saline, the nerve falls directly into that state of excitation which, though at first too weak to express itself in twitches of the muscle, appears later on as a vigorous tetanus. Just at the moment at which the excitation is latent, break twitch II, or Ritter's tetanus, may be produced even by weak currents. The

highly favourable action of dilute alcohol to the appearance of break twitch II must surely bear a similar interpretation, although Eckhardt and Kühne limited its excitatory action to 80 %. Mommsen, however, has not infrequently observed twitches of the muscle on treating the nerve with comparatively dilute alcoholic saline (20 vol. %), and the same is confirmed by Biedermann's observations.

The statement that the discharge of break twitch II, as well as the appearance of Ritter's tetanus, is associated with the presence of latent excitation in the nerve, finds striking confirmation in the fact that break twitch II, with all its characteristic properties as above described, may be elicited in nerves which have been thrown by weak tetanisation into a state of latent excitation (Grünhagen's process).

To this end it is only necessary to tetanise the central end of a sciatic nerve, divided from the spinal cord, or still connected with it, at a distance of coil which is only just able to excite. If a lower point of the nerve is simultaneously excited with weak descending constant currents, opening twitches will not fail to appear at a moderate duration of closure; and these twitches are, in every respect, equivalent to break twitch II, since, like the latter, they make a delayed entrance, and are in a marked degree dependent on duration of closure. If current intensity is strengthened, the break twitches become more extended, and finally pass into tetanus, which, like the twitches, is delayed in its entrance. The identity of this opening effect with that described above as secondary is indisputable, seeing that here too the opening of weak currents is followed by a double effect, if the disposition to primary opening twitches is previously induced by brief closure of a stronger current. This effect either consists in double twitches, or else break twitch I appears as introductory to Ritter's tetanus.

If the nerves are excited during weak and intrinsically ineffective tetanisation by an ascending constant current, there will, in proportion with the intensity of the latter, be either a reinforcement of the closure twitch or closure tetanus, never, however, an opening excitation.

The application of a fairly strong chemical excitant has substantially the same effect as weak tetanisation above the point of nerve excited by the constant current. Glycerin is

especially appropriate. In favourable cases a weak descending current discharges break twitch II shortly before the explosion into tetanus. A similar experiment was made by Grünhagen (36). But if this proves that break twitch II and Ritter's tetanus (as well as the closure tetanus) are in many cases due, not, as Pflüger thought, to disappearance of anelectrotonus (or entrance of katelectrotonus), but to latent stimuli, which, in themselves inadequate to excite the muscle, first become effective when the excitability of the nerve is raised after the disappearance of anelectrotonus (or during an existing katelectrotonus)—it must be admitted that in many cases an adequate opening excitation of the same character appears without any previous state of latent excitation (cooled nerves). Nor is this surprising in view of the relations between rise of excitability and excitation, as described above. On the other hand, the nature of break twitch I is still unexplained, although the conditions of its appearance are known more precisely than before.

Arguing from experiments in which break twitch I appears immediately after making a (mechanical, chemical, or thermal) cross-section in the close proximity of the anode, it follows that the demarcation current developed by this injury must be in causal connection with the appearance of break twitch I. Yet this cannot be in the sense that the raised excitability in the vicinity of the cross-section (the cause of which will be discussed below) renders weak opening stimuli effective; for this hypothesis seems to be sufficiently contradicted by the foregoing data. Grünhagen's view that the appearance of the make twitch, when a fresh section is applied to the nerve near the anode, is to be regarded primarily as a "product of summation" ("on the one hand, of the intrinsically inadequate excitation, consequent on the opening of the descending current," *i.e.* the anodic stimulus; "on the other, of the continuous, weak, mechanical stimulus of the incision"), must be regarded as disproven. For—apart from the fact that an after-effect of simple division, lasting for hours (and the disposition to the discharge of break twitch I does last that time in the vicinity of the cross-section), is highly improbable—it may further be urged against Grünhagen that the effects of the make excitation would then have to be proportionately strengthened, with uniform position of electrodes, and ascending direction of current, which is not the case. We have

already seen that the same effect appears in striated muscle. There we had direct proof of "false" break twitches caused by internal short-circuiting of the demarcation current, compensated during closure of the battery current in the leading-off circuit. It is natural to apply the same explanation to the primary break twitch from the transverse section, in nerve-excitation. This was actually done by Grützner (41) and Tigerstedt (41), who only go too far, inasmuch as they deny *any real* break excitation due to fall of the current, and assume that every so-called opening excitation is constitutionally an effect of closure, deriving from an interference between exciting current and nerve current, which last may be either a demarcation or a polarisation current.

As against this view it must be maintained that in nerve, as in muscle, *there is a true opening excitation,* viz. a reaction of the excitable substance towards the changes produced by current (at the anode). The interference effects between exciting current, and pre-existing differences of potential, which underlie the "false" opening twitches, can only be dealt with later, in discussing the electromotive action of nerve.

Since (as appears directly from the above) the effects of exciting motor nerves with the constant current depend essentially upon the relations of excitability in the nerve, we should anticipate a fairly complicated reaction from a nerve-muscle preparation, inasmuch as it presents a multiplicity of functional elements, differing in excitability—as was shown, *e.g.,* for the rheoscopic frog's leg with flexors and extensors supplied by a common nerve-trunk, and in a far higher degree in the crayfish claw. As regards the first case, it may be remarked that, according to Grützner (42), the excitation of the frog's sciatic with currents of increasing intensity excites quite different muscles at closure, and at a later period. If there is eventually an adequate break excitation, those muscles alone twitch which first became active at closure. The opening stimulus thus acts here (with stronger currents) like a weak closing excitation. The same may be observed on man when the electrodes of a sufficiently strong battery are applied to the *sulcus bicipitalis internus.* At a certain strength of current, the muscles that twitch at make and at break are different (flexion of hand at make, pronation at break).

2. *Excitation of Nerves in Crayfish*

On the *crayfish claw,* under certain conditions, the excitatory effects of the constant current may be remarkably developed (Biedermann, 43). It has already been stated that with tetanising excitation of the claw-nerve, the tonically contracted adductor muscle relaxes at about the same comparatively low strength of current at which the abductor contracts vigorously; while strong currents, again, throw the former into tetanic contraction, the abductor either suffering no visible change of form, or, if there is any tonus, becoming relaxed. Hence there would appear to be a complete antagonism of excitatory conditions in the nerves corresponding with the two muscles.

The results of excitation with the constant current, on the other hand, are much more complicated. In the first place, there is never a "neutral zone" of current strength as defined above, although striking and perfectly regular differences of action between currents of different strength are by no means wanting. In agreement with the excitatory reaction on tetanising the nerve by means of alternating currents, *e.g.*, we find with closure of a battery current that the excitatory effects predominate or appear alone in the abductor, the inhibitory effects at the adductor, with low intensity of current, while with stronger currents the contrary effect appears. In detail, however, the effects are far harder to analyse, because at each adequate excitation both impulses (excitation and inhibition) usually appear, so that in tracing the changes of form in one of the two tonically contracted muscles, highly complicated curves may arise, which are only intelligible on the ground of the previous data.

The effects of excitation are best seen in the atonic adductor muscle, where the results agree throughout with experiments on other nerve-muscle preparations, and correspond perfectly with Pflüger's law of contraction. Medium currents here work independent of the direction in which they are passed through the nerve, exciting both at make and at break, while a strong descending current excites at make, a strong ascending current on the contrary at break only. It is to be remarked for these experiments that every stronger excitation gives rise to a more or less prolonged tetanic contraction of the muscle, so that *persistent excitation by the constant current* is here the rule (*supra*).

Similar experiments on the atonic abductor muscle show that, apart from other differences to be discussed below, it is, as a rule, excited by much weaker currents than the adductor muscle, while strong currents under some conditions prove wholly ineffective, at other times discharging contractions considerably weaker than those from currents of lower intensity. This last paradox, however, is not invariable, and cannot even be termed a frequent occurrence.

Direction of current seems to be of importance in all experiments on the muscles of the claw, inasmuch as the closing excitation appears in the majority of cases with ascending, rather than with descending currents, while the contrary is true of the opening stimulation. The cause of this reaction must be sought less in any special property of the nerve-fibres than in the fact that with the above conditions of experiment, current density at the two electrodes is not equal, but is less at the contact that lies towards the periphery than at the central contact. This is due to the form of the joint to which the (thread) electrodes are applied, since the diameter of the joints increases considerably towards the claw. The above difference may be neutralised, or even reversed, by merely passing the threads as near as possible to the nerve, which runs along the inner surface of the limb, or by using a more basal joint for excitation.

All doubt as to the validity of Pflüger's law of excitation for the nerves of the adductor as well as the abductor muscle is removed by simply excluding the central electrode, as will be shown below.

While in atonic muscles treated by the above method the effects of excitation by the constant current are tolerably uniform, there is, along with conformity of detail, a surprising variety of effect, on exciting preparations from either of the two claw muscles, when there is a more or less well-developed tonus. This is intelligible since each single stimulation affects the muscle in an exactly contrary direction, and thus, as will be shown, produces opposite changes of form. Excitatory or inhibitory effects preponderate according to the state of the preparation, and the strength and direction of the exciting currents.

The preparations of the adductor muscle which most conveniently show the dependence of inhibitory and excitatory action from the constant current, upon its direction and in-

tensity, are such as are in a state of moderate tonic contraction, and therefore react by corresponding changes of form to both effects of excitation.

If with increasing intensity of current the preparation is excited with alternately ascending or descending currents, or with uniform direction of current, there are, as a rule, certain obvious characteristics of the mode of reaction which—given the

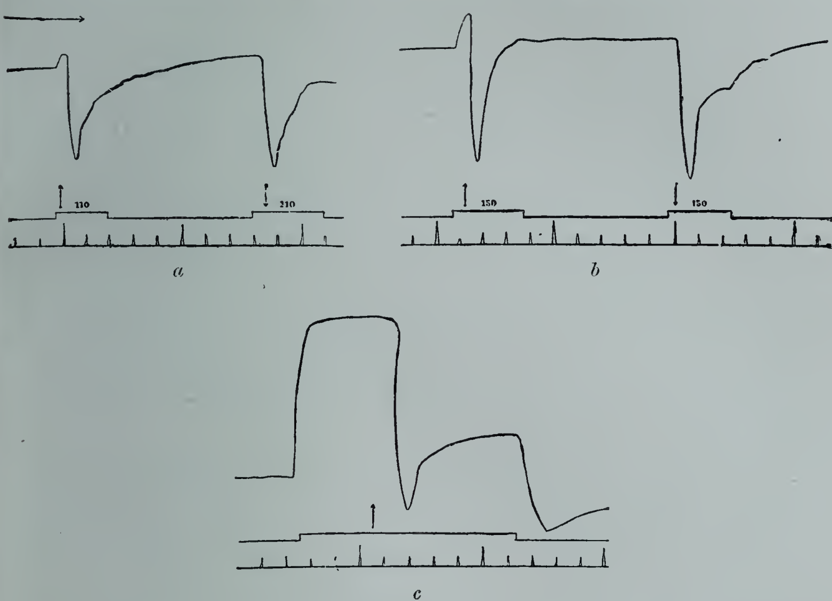


FIG. 195.—Adductor of crayfish claw. Excitation of nerve with constant currents. The existing tonus is little if at all increased by closure of weaker currents (a, b), which essentially inhibit it. Closure of a strong current on the other hand $=c$.

previous data *re* tetanisation of the nerve—distinguish the adductor muscle sharply from the abductor.

In the first place, it is evident that in preparations of the former muscle weak currents and medium currents have a predominantly inhibitory action, while with stronger currents the effects of excitation preponderate, or alone appear (Fig. 195, *a*, *b*). This is expressed, on the one hand, in the fact that the augmentation of tonus that invariably corresponds with the moment of closure, *i.e.* shortening of the muscle, increases with increasing intensity of current to a certain upper limit, which (from the mechanical conditions of the experiment) is

not necessarily the maximum of contraction; while, on the other hand, the duration of closure tetanus increases also, thus accounting for the fact that the obvious inhibition (relaxation) at each single stimulus begins so much later after the beginning of excitation (closure) in proportion as the current is strengthened.

If the successive alterations which occur in contraction are considered synthetically, there appears to be a gradual transition from increasing and more or less extended twitches to definite and prolonged closure tetanus; which recalls the similar reaction of the relaxed atonic muscle under the same conditions. Make twitches of characteristic brevity occur not infrequently at a certain strength of current, their curves being distinguished by a very sharp apex: these presumably represent the effects of inhibition following rapidly upon closure, since the curve of make twitches under normal conditions is extended.

The beginning and end of a series of experiments on atonic adductor muscle are usually characterised by single (and opposite) signs of excitation, with many intermediate transitions of action, which, according to the strength of current, exhibit a regular antagonism between excitation and inhibition, contraction and relaxation.

As shown by all previous experiments, inhibitory action appears singly (in indirect excitation of the adductor muscle by constant currents) at comparatively low intensity of current only; while very strong currents have an exclusively exciting action—at all events, this is the rule immediately after closure.

It should be further observed with regard to the abductor muscle of the crayfish claw, that when once the exciting current is sufficient to produce a perceptible reinforcement of the existing tonus at closure, *this effect under all circumstances precedes the subsequent diminution of tonus due to inhibition.*

In the curve this only appears at first as a slight rise, previous to the deep depression described by the lever in consequence of the sinking (from inhibition of tonus) of the free, and downward directed, arm of the claw. With each stronger stimulus, the consequences of excitation are seen more plainly, while those of inhibition are at first equal, and then, owing to the increasing closure tetanus, make a more and more delayed entrance.

The curve at first rises steeply from the initial abscissa (which

corresponds with the existing tonus), and then, sooner or later, makes a sudden drop below it (Fig. 196), either rising again immediately, or more slowly, after a certain interval, so that the lever often recovers its initial position during closure, in other cases, however, only when the circuit is opened. It not infrequently happens, at a given strength of current, that the shortening of the tonic muscle, on closing the circuit, corresponds both in magnitude and duration with the subsequent relaxation, so that the first section of the curve above the abscissa is almost equal with that of the lower half (Fig. 196). In current-intensities below this limit, the second half of the curve seems generally to preponderate, while beyond it the effects of excitation come more and more into play at the expense of the inhibiting action—so that the first section of the curve is highly characteristic.

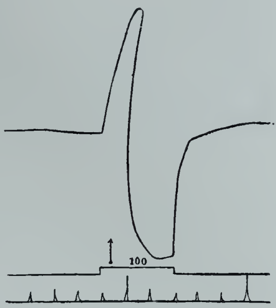


FIG. 196.

The inhibitory effects are often so indefinite, that their existence as independent signs of stimulation might easily be overlooked, without some knowledge of the action of weaker currents; and they might be viewed merely as fatigue-effects from the immediately preceding persistent excitation. This is indeed contradicted by the fact (as insisted on above) that re-entry of the more or less strongly inhibited tonus usually occurs during the passage of the current; while, moreover, the break of a stronger current not unusually inhibits to the same extent as the closure of a weak current. On opening the exciting circuit a fall of the curve similar to that previously obtained during closure (Fig. 195, *c*) is apparent.

We thus learn that the reaction of the tonically contracted adductor muscle, on exciting its nerve with the constant current, is characterised throughout (with increasing strength of current) by depression of inhibitory effects in favour of excitatory action, until the inhibition becomes imperceptible. In the abductor muscle the contrary occurs, owing to its much stronger and more persistent tonus. This is evident from comparison of the curves (Figs. 195, 197), which, though recorded as far as possible under uniform conditions, are in many respects exactly opposite.

While the tonus of the adductor muscle is, as a rule, inhibited by minimal effective currents, without any perceptible excitation, either previously or during prolonged closure, the first effect of weak stimuli upon the abductor muscle is pre-eminently a strengthening of the existing tonus; and there is, in this particular, complete agreement between the effects of stimulation with tetanising alternating currents and with the battery-current. Even slight augmentation of the latter, however, in the one as

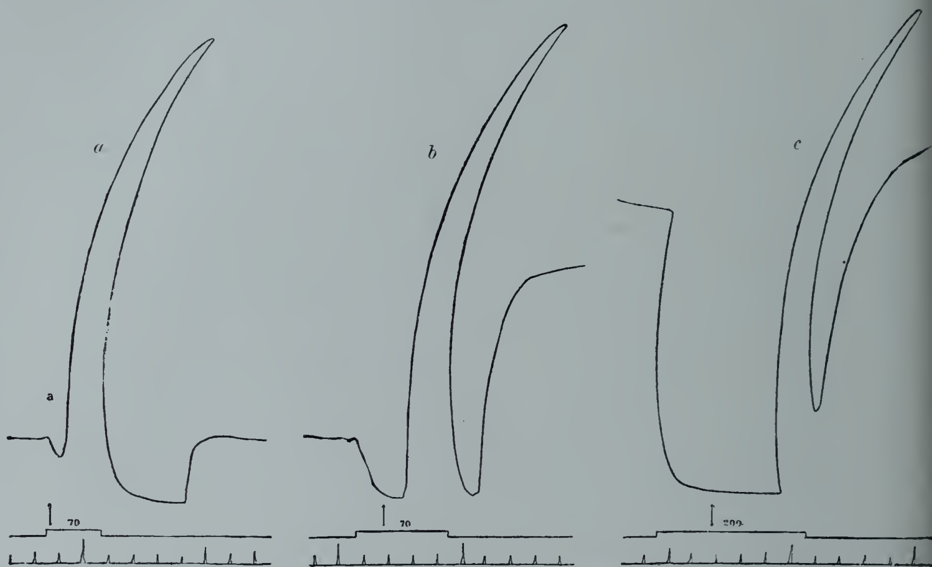


FIG. 197.—Abductor muscle of the crayfish claw (tonic); stimulation with constant currents of increasing intensity; augmented inhibition as primary effect of excitation. Time-marking in seconds.

in the other, brings out the striking dissimilarity, that each single stimulus now produces double action. But while in the adductor muscle excitation invariably precedes inhibition, the contrary occurs in the abductor. At the moment of closing the exciting circuit, excitation (contraction) in the one case, inhibition (relaxation) in the other, makes a delayed entrance, and must in each case be regarded as the primary effect of the current.

As in the adductor muscle the consequent excitation seems, at its first appearance, to be merely indicated, as an independent constituent of the curve, so the same holds good of the effects of inhibition, with indirect excitation of the abductor muscle.

Fig. 197, *a*, shows, after an insignificant fall of the curve beginning at the moment of closure, a marked rise, in consequence of the now developing make excitation, leading at *b* and *c* to a permanent reinforcement of the initial tonus. With the less favourable descending direction, the same weak current produces excitation only at closure, without previous inhibition, *i.e.* acts as a weaker stimulus. The same gradation of effect with the two directions of current is in most cases more or less plainly visible on stimulating with alternately ascending and descending currents. With increasing strength of excitation, the primary inhibition becomes more and more conspicuous, the curve falling deeper on the one hand at closure of the current, and on the other rising again the more slowly to the abscissa, or passing beyond it, in proportion with the intensity of the current.

Seeing that with indirect stimulation of the adductor muscle by not unduly weak constant currents, *inhibition*—with stimulation of the abductor muscle by strong currents, on the other hand, *excitation*—makes a more or less delayed entrance after closure (as expressed in the corresponding changes of form in the muscle), insufficient duration of closure in either case will give the impression of single, or negative, effects of excitation. This is more especially the case in preparations of the abductor muscle, where, owing to want of tonus, the inhibitory effect, as expressed directly in changes of form in the muscle, is absent.

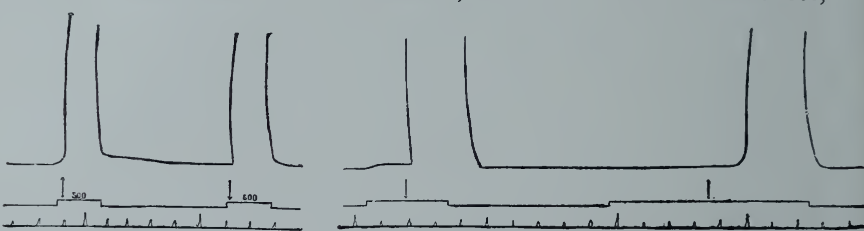
Such inhibitory action is then apparent only in a retardation of the latent period, which may, under certain conditions, last for several seconds—a fact which gives a characteristic form to these curves, and indicates their origin from the abductor muscle (Fig. 198, *a*, *b*). That this is really no more than the effect of an inhibition, antecedent to the excitatory action of the current, is most plainly seen in cases in which the muscle is excited once with uniform strength of current, while there is still a perceptible tonus, and again later in the relaxed condition.

In both cases the make contraction is retarded in about the same degree, but while in the one, closure of the circuit produces a visible diminution of tonus, inhibition is expressed in the other solely by the lengthening of the latent period.

It follows that the inhibitory action of the constant current antecedent to excitation may be demonstrated in almost every

single case, even with comparatively weak currents, since a perceptible delay in the appearance of contraction (visible even at a slow rate of the recording surface) is wanting, as a rule, only in the weakest, minimal currents. The time-value of the delay differs much in different preparations, and, as a rule, diminishes in the same preparation with frequent repetition of stimulus, even when the excitatory action of the current shows no sign of diminution.

Just as the inhibitory effect of stimulation is sometimes very apparent in preparations of the adductor muscle (according to its state), while in other cases it is merely indicated, or quite imperceptible, notwithstanding an equal development of tonus—a variation that may essentially be due to altered conditions in the muscle: so in the abductor, we find similar differences,



a *b*

Fig. 198.—Abductor muscle of crayfish claw (atonic); excitation with (*a*) weak and (*b*) strong battery currents; in the last case there is a pronounced delay in the make contraction.

although the inhibitory action here takes effect, as a rule, far more certainly than in the antagonist muscles.

The excitatory action of strong constant currents in the adductor muscle (*supra*) so far preponderates over its inhibitory effect that the latter only appears very exceptionally with strong excitation, when a transitory relaxation may sooner or later interrupt the closure tetanus. This is not equally true of the abductor, where, even with strong currents, the inhibition (which, as regards dependence on strength of stimulation, corresponds with excitation in the antagonist muscles) is almost regularly interrupted by the succeeding excitation in the course of a long closure; which excitation—like the inhibition of the adductors—first effects entrance when the strength of the stimulus begins to decline during the passage of the current. This last fact may well cause the differences of effect on exciting with constant or with tetanising alternating currents.

As regards the break excitation, it should be observed that it requires stronger currents (here as everywhere) than the make effect, and may, like this last, produce opposite changes of form in the muscle under certain conditions. In consequence of the inferior strength of the opening stimulus, however, it only *excites* the muscle in the majority of cases, and seldom reaches sufficient proportions to *inhibit* a pre-existing tonus. But if in such a case the exciting action of the current fails to find expression, the effects of stimulation both at make and at break of the circuit may consist in a transitory relaxation of the tonically contracted muscle: the curve then presents two depressions, one beginning at closure, and disappearing only during the passage of the current, the other less considerable—corresponding with the break of the exciting circuit (Fig. 199).

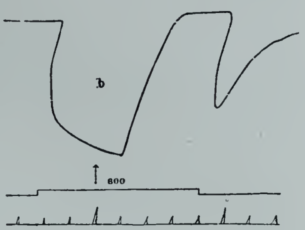


FIG. 199.

In view of the double, partly inhibitory, partly exciting effect of stimulating the two muscles of the crayfish claw with the constant current, the important question arises whether—under the presumption of pure polar action of current—the two effects, at make on the one hand, at break on the other, proceed from the same electrode, or whether there is an antagonism between the respective discharges of excitation and inhibition.

It has already been stated of the atonic adductor muscle that the order of excitatory effects corresponds throughout with Pflüger's law; *i.e.* both on applying very strong currents, and after excluding the influence of the central electrode by partially killing the nerve, the descending current takes effect at make, the ascending current at break only of the circuit.

Since in the first case—owing to the enormous resistance in the exciting circuit, and low density within the part traversed—the current must be of very considerable intensity in order to obtain the third stage of Pflüger's law (with unpolarisable electrodes), the second of the methods given above seems the most appropriate.

By this it is easy to ascertain, with given intensity of current for both adductor and abductor muscle, that *inhibition*

as well as excitation proceeds at make from the kathode, at break from the anode.

It suffices to divide the claw-nerves in the proximity of the central electrode, or to kill a certain portion of them *ab initio* by warming (dipping the limb of the claw in hot water almost to the point of excitation). This is obviously liable to affect the tonus of the muscle, so that it does not always yield satisfactory results; in other cases, however, the experiment is perfectly successful.

VI. Polar Excitation of other Nerves and specific Nerve-Endings

Donders (44) has established polar action in the *inhibitory fibres of the cardiac vagus* according to Pflüger's law, by graphically recording the heart-beats. With adequate closure or opening of a constant current there is plainly seen, after a short latent period, to be lengthening of the succeeding, and especially of the next two pulsations; and with increasing strength of current the order is as follows—ascending make, descending make, descending break, ascending break. The effects of ascending make and descending break soon reach a maximum, after which they decline, and fail even with strong currents, thus corresponding exactly with the law of contraction.

In view of the sluggishness of most *smooth muscles*, and their consequent inability to react to a single brief stimulus, we should *a priori* expect the manifestations of the law of polar excitation to fail altogether, or at most to appear exceptionally, with indirect excitation. Thus a single closure or opening of the constant current produces no effect on the cervical sympathetic, while repeated closure and opening result in unmistakable constriction of the vessels of the ear (in rabbit). On the other hand, Pflüger's law is easily demonstrated on the comparatively quickly reacting muscles of the sphincter iridis (of cat). So, too, on the mantle-nerves of *Eledone* (v. Uexküll, 45). The closure and opening of medium currents cause contractions with both ascending and descending direction. Closure of a strong descending current gives tetanus throughout the period of closure, but has no effect with ascending direction; opening of the circuit in this case produces prolonged opening tetanus. The descending closure tetanus is often rhythmical.

Pflüger's law can also be demonstrated on *secretory nerves*, if the galvanic alterations in gland-cells be taken as the index of excitation. This is easily shown on the frog's tongue if the glosso-pharyngeal nerve is excited (Biedermann, 8). Here again we see that constant currents are much more appropriate for the excitation of secretory nerves than single induction shocks, which with even powerful intensities produce hardly any modification of the lingual current, while the single closure of a medium battery current invariably produces visible consequences. This striking disparity of action is undoubtedly, in either case, caused solely by dissimilar *duration* of the currents—thus not merely testifying against the infallibility of du Bois' "universal law of excitation," but proving the accuracy of the view of Grützner and Schott, viz. that rapid stimuli excite the quickly reacting, slow stimuli the more sluggish end-organs. If, with a strong ingoing lingual current, 3–6 Dan. are closed in the descending direction, after previous compensation of the current, there will regularly be—after a short latent period (1–2 sec.)—a monophasic negative variation, which is often of considerable strength, persisting for some time during closure, and vanishing rapidly when the circuit is broken; whereupon, if the current is not too strong, the break excitation appears as a delay, or even as a brief arrest of the backward impulse. This is usually still more plain on exciting with ascending currents, closure of which produces the same monophasic, albeit essentially weaker, negative variation as the descending direction. If very strong currents are employed, the effects may correspond throughout with the third stage of the "law of contraction"; since with the descending direction a "closure variation," with the ascending direction an "opening variation," alone appears. As we should anticipate, the alternate closure of opposite currents by means of a Pohl's reverser invariably results in an excessively strong variation of the current of rest.

Pflüger (46) was again the first to investigate the action of currents of different direction and intensity upon *centripetal* (*sensory*) *nerves*, using the reflexes discharged as indications of excitation. The frogs were weakly strychninised, and current then led through the isolated sciatic—the unskinned leg remaining attached to the nerve, to avoid artificial cross-sections. The presumptions of Marianini and Matteucci for strong currents were entirely realised. Reflexes were excited only by closure

of ascending and opening of descending currents, because in the first case the katelectrotonic, in the second the anelectrotonic part of the nerve communicated directly with the spinal column; the leg connected with the nerve, on the other hand, twitched according to the law of contraction only with the two opposite stimuli. With medium currents, all four stimuli were reflexly responded to, as previously pointed out by Matteucci. Setschenow and Hällsten (46) have since investigated the same question, arriving at essentially the same results.

The consequences of exciting *mixed centripetal nerves,* which consist of antagonistically working fibres, e.g. *the vagus,* are much more complicated. Grützner discovered that the closure and passage of constant ascending currents, and in a less degree the opening of descending currents, had an inhibitory, expiratory effect upon respiration, while opening of ascending and closure of descending currents remained ineffective. Langendorff and Oldag (7) have recently submitted these facts to more accurate investigation, finding that an ascending constant current, sent into the central end of the vagus, "in all cases influences respiration in the *expiratory* direction; *i.e.* it either induces a longer expiratory arrest, or retards the breathing by inducing expiratory pauses." And this is the case not merely at the moment of closure, but throughout prolonged passage of current. Breaking the current in most cases induces a visible *inspiratory* effect, expressed either in a deepening of inspiration, or in a short inspiratory stoppage. The closure and passage of the descending constant current were always found by Langendorff and Oldag to be less effective than those of the ascending current, and that in an antagonistic sense, *i.e.* inspiratory; while opening the circuit again produces an inspiratory standstill.

"*Inhibition of respiration (expiratory) is therefore produced by closure of the ascending and opening of the descending constant current; excitation of respiration (inspiratory) by opening of the ascending and closure of the descending current.*"

The same (expiratory) action as with ascending constant currents may also be produced on thoroughly narcotised animals by interrupted constant currents of uniform direction, especially where the frequency of interruption is small, and the closure of prolonged duration. Inspiratory effects, on the other hand, not only appear with closure of descending persistent currents, but still

more with rhythmical excitation at uniform direction of current. A positive interpretation of these data is hardly possible without further investigation ; in any case, Langendorff's assumption that "simple galvanic variations of current, and the passage of the current, are merely inhibitory, while oscillatory variations are excitatory in action"—and that "the excitation which proceeds from the lower, distal electrode implies a tetanising element"—needs further corroboration.

Great theoretical interest attaches to experiments on the *polar excitation of the higher sensory nerves* by the constant current, *sensation* here serving as the excitatory reagent. The earlier electricians collected a fund of experimental data in this department, although the interpretation of their facts is very dubious. Those relating to the *taste-sense* are the most obvious. Here, as in all other cases, it must be noted that *excitation of the isolated sensory nerve involved is not possible, the peripheral end-organ (sensory epithelium) being under all circumstances excited with it.*

The first and weightiest conclusion from the older experiments is as follows: When an electrical current is passed through the tongue, an acid taste is perceived at the point where current enters (anode), and a different taste, usually described as alkaline, at the point where it leaves (kathode). Volta, however, described the latter as being merely somewhat alkaline, sharp, and rough, approaching to bitter. These two sensations, one of which (kathodic) is always much weaker than the other (anodic), continue as long as the current is passing, and are perceptibly reversed (as observed by Ritter) when the circuit is opened. Rosenthal (47) was unable to discover this, finding merely that the acid taste continued for a short time after breaking the current, while the alkaline trace quickly disappeared. At the same time v. Vintschgau (47) confirmed the observations of Ritter—the predominant acid being converted into a faintly metallic taste at the moment of opening the current, when the kathode was applied to the root of the tongue.

As early as 1793 Pfaff discovered the relation between the difference in electrical taste according to the disposition of the metals on the tongue, and the difference in contraction according to their distribution in nerve and muscle; and the possibility at once presents itself of direct comparison between the qualitatively different, and in a certain sense antagonistic, polar effects, on excita-

tion of the sensitive lingual mucosa, and those exhibited by so many other excitable substances—the more so since the contrast between closing and opening effects finds complete analogy in the law of polar current action.

Further details of electrical sensations of taste are subjoined from the recent investigations of Laserstein (47). Just as there are individual differences in the sense of taste, so there are individual variations in sensibility to the current, varying in the same person at different times, and in different individuals. As might be expected from the greater intensity of the anodic acid taste, the liminal value for the ingoing (acid) current lies considerably lower than that for the outgoing current. With non-polarisable electrodes, the liminal value of current for the acid taste was about $\frac{1}{156}$ milli-ampère. This very low figure is undoubtedly due to the *high specific excitability* of the organ of taste towards constant currents, in which respect it far exceeds all other sense-organs. Oscillations of current produce no visible augmentation of gustatory sensations.

The electrical taste has been very differently interpreted. One question is of primary importance: *Do the sensations of taste arise from the direct stimulation of the taste-nerves by the current, or are they caused indirectly by electrolytic decomposition of the fluids in the mouth?* We know that when an electrical current passes through a fluid containing salts of alkalies—instance the fluids of the mouth which are moistened by the lingual mucosa—the salts are decomposed; the acids coming off freely at the anode, the alkalies (which are immediately oxidised) at the kathode. The presence of free acids at the positive, of free alkalies at the negative pole, would thus very simply account for the acid taste at the latter. Against this explanation it may be urged that the sensations of electrical taste are also present when the current does not enter and leave by metallic electrodes (in which case electrolysis is inevitable), but is led through the tongue by other electrolytes, or by non-polarisable electrodes; this experiment has been tried by Monro, Volta, and, more recently, by Rosenthal (47).

"Rosenthal brought two persons into contact by the tip of their tongue, the one holding the positive, the other the negative pole of a battery, with moist hands: the first person has an alkaline, the second an acid taste. Here the two persons are under

identical conditions, except as to the direction of the current in the tongue. This is opposite in the two subjects, so that they have opposite sensations, although their tongues are in contact, and the same capillary layer of fluid covers the one as well as the other. Rosenthal, moreover, sent the current of 1–4 Dan. through the body and tip of the tongue, both poles consisting of zinc plates dipping into two vessels of zinc sulphate: these were connected by siphon-shaped tubes with two other vessels, one filled with saturated salt solution, the other with distilled water. A pad of filter-paper, also soaked with distilled water, projected from the latter. On dipping one hand into the saline and touching the pad of filter-paper with the tip of the tongue, the current either passed from tongue to pad, or *vice versa*—as regulated by a reverser in the circuit. A strip of red litmus-paper was laid on the pad so that both were in contact with the tongue. The red paper turned faintly blue when touched by the alkaline fluid of the mouth—blue remained unaltered. On closing the current there was a distinct sensation of taste, but the colour of the two papers remained unchanged with either direction of the current" (v. Vintschgau, *l.c.*).

Against the cogency of these experiments there is good evidence to indicate that the electrical taste depends not upon electrolysis of the fluids in the mouth, but upon direct excitation of the taste-nerves. It must in the first place be remembered, as pointed out by du Bois-Reymond, that *polarisation occurs at the interface of dissimilar electrolytes* (*Ges. Abh.* I. p. 1), so that under given conditions there may be a separation into acids and alkalies (Hermann, 48). There is no reason why the electrical taste should not be derived from electrolytic processes *within the lingual tissues*, the direction of current being indifferent. From this point of view, Volta's experiment with a tin beaker filled with lime (34, iii. 2, p. 185) loses all point; as also, according to Hermann (*l.c.*), the second of Rosenthal's experiments, as cited above. Neither, however, is the electrolytic theory tenable, as appears from electrically exciting other sense-organs, and also from the opposite after-sensations on breaking the current when the tongue is stimulated. Hermann pointed to this last difficulty (*l.c.* p. 538) when he remarked that an ingoing depolarising current was discharged in the polarised organ at the moment of breaking an outgoing current; this current is

only capable of neutralising the alkali present, and not of forming acid, so that there should be no acid after-taste at the kathode—which does, notwithstanding, make its appearance.

If we attempt to determine the phenomena in question as the consequences of direct polar excitation of nervous organs, we meet with an initial difficulty in deciding which portion is primarily excited by the current flowing in alternate directions. Laserstein has contributed to the solution of the question in the communication above quoted. It is known that cocaine has the property of abolishing the excitability of most peripheral sensory nerve-endings, the sense of taste not excepted. In Laserstein himself this was not fully abolished by cocaine—disappearing first for bitter and sweet, then for salts, but not entirely for acids, though enormously reduced for these also. A trace of acid electrical taste remained with an ingoing current, but the full strength of a Dan. was then required, whereas previous to the application a current with 5000 ohms principal, and 210 deriving, resistance was sufficient. For Hermann, cocaine abolished all taste, including the electrical. This experiment proves essentially that the structures, upon alteration of which by current depends the sensation of taste, are situated in the *extreme periphery.* The strength of current that produces these sensations, as compared with other physiological persistent effects of stimulation, is so low that its density can only be adequate immediately beneath the electrode.

If the trunk of the nerve also were traversed, there would each time be other sensations in the region of the cervical nerves. Moreover, there can only be a question of orientated passage of current through nerve-fibres or end-organs immediately under the electrode, and it thus becomes intelligible that when both electrodes are applied to the tongue there should be an acid taste under the one, an alkaline taste under the other. *The electrical taste therefore depends exclusively upon passage of current through the end-organs, or the ultimate nerve-endings radiating in the mucosa.* According to the law of specific energy, by which each sensory nerve, wherever and however excited, produces but one and the same specific sensation, the results from electrical excitation of the tongue seem to coincide with and witness to this principle. But if the law is strictly adhered to, all nerve-fibres being regarded merely as indifferent conductors

of excitation, the difference in effect being occasioned by the central or peripheral end-organ, the fact that the two directions of current call out *different* sensations by their excitatory action on the nerve, or its end-organs in the tongue, is contradictory.

Whether we assume, *e.g.*, that the ascending current excites the acid-reacting fibres only, or mainly (which is highly improbable), or that the action of the ascending current in each fibre differs from that of the descending, the law of specific energy is inevitably contravened if it is construed in the preceding sense. On the other hand, there is little difficulty in bringing facts into line with theory, to which indeed they appear the inevitable corollary, if the effects of polar excitation of the taste-nerves are viewed as parallel with the antagonistic polar action of the electrical current in other excitable substances (muscle, nerve). There is only one point in which the consequences of the electrical excitation of centrifugal nerves and muscles differ from those in sensory nerves, viz. that in the last case the end-organs (central ganglion-cells) react by qualitatively different (antagonistic) sensations to the changes produced at the kathode, as well as at the anode, whence it follows that centripetal nerve-fibres must transmit the two opposite kinds of alterations.

According to the view developed by Hering it may be presumed that a sensory nerve gives rise to opposite sensations, according as the dissimilatory or assimilatory process predominates (Hermann, *Pflüger's Arch.* xlix. p. 536). If we add that the former is always developed persistently at the kathode, the latter at the anode, the phenomena of electrical taste find a simple explanation without prejudice to the law of specific energy. Moreover, the phenomena consequent on the electrical stimulation of other sense-organs will then be satisfactorily accounted for, since, as Hermann pointed out (*l.c.* p. 537), there is no difficulty in deriving opposite sensations from opposite directions of current. In most cases the *peripheral end-organs* must be understood, since these alone, as a rule, are perceptibly polarised under experimental conditions. The ingoing current causes the assimilatory, the outgoing current the dissimilatory change to preponderate; but it must always be assumed that the electropolar sensations are mutually complementary, or (which amounts to the same thing) stand in relation of contrast (Hermann, *l.c.*).

This is even more plainly seen in the *electrical excitation of*

the eye than in the taste-sense. The following facts are taken from Helmholtz's latest communication (49).

If the eye is excited by variations of current of adequate intensity, one electrode being applied to the forehead or closed eyelids and the other to the neck, more or less pronounced flashes of light appear across the entire field of vision, while if galvanic currents are employed they occur both on closing and on opening the current.

Stronger currents are usually required to produce a persistent effect from a steady constant current, than for make and break flashes. In order to avoid these, as also twitches of the muscles on making and breaking the current, Helmholtz found it advisable to place two metal cylinders, surrounded with paste saturated with salt solution, and connected with the two poles of a Daniell battery of 12–24 cells, at the edge of the table where the subject was sitting. The forehead is firmly applied to one cylinder, while the hand touches the other, and if this is done gradually the effects of alternating the currents are quite inconsiderable. The direction of current varies according as the forehead touches now one and now the other of the cylinders. "If a weak ascending current is led through the optic nerve, the dark field of vision of the closed eye becomes brighter than before, and takes on a greyish-violet hue. The point at which the nerve enters looks at first like a dark circular disc in the bright field. The illumination soon diminishes in intensity, and disappears altogether on breaking the current. As the field of vision becomes obscured, the previous blue tinge is replaced by a contrasting reddish yellow from the subjective light of the retina." "On closure of the opposite, descending direction of current there is a marked effect, *i.e.* the field of vision (which is illuminated only from the intrinsic light of the retina) usually becomes darker than before, and appears to be reddish yellow; the entrance point of the optic nerve alone stands out as a bright blue disc upon the dark fundus. On breaking this direction of current the field of vision becomes bright again, and bluish white in colour, while the optic disc is obscure." Other observers have described the phenomena somewhat differently; the views of Ritter, Purkinje, Helmholtz, and Brenner are summarised (after Rossbach) in the following table.

State of Current.	Ritter.	Purkinje.	Helmholtz.	Brenner.
		I. ANODE TO THE EYE = ASCENDING DIRECTION OF CURRENT		
At closure of circuit.	Increased brightness of field of vision (positive light state); sensation of shining blue colour; flash.	Perception of light as a yellow mist across an obscure fundus. Optic disc bright, clear violet; at visual axis a square dark spot, surrounded with a quadratic yellowish band of light, followed by a dark interval, and then another less bright yellow band; the extreme periphery of the field is a faint, pale violet.	With weak currents the dark field of vision of the closed eyes becomes brighter than before, and assumes a whitish-violet tint; the optic disc at first appears as a dark circle in the clear field.	A yellowish-green disc appears in the fundus of the eye upon an obscure background, surrounded by a clear blue ring, which seems at first to be larger and brighter. The sudden appearance of this initially brighter and larger ring gives the impression of a flash.
During closure of circuit.	The state of positive light continues during closure of the circuit.	...	Intensity of illumination declines rapidly.	The bright blue circle becomes smaller and smaller, grows dim, and finally disappears altogether. The central phenomenon outlasts it for a short time, but eventually disappears also.
Opening of circuit.	Sensation of red colour (darkening of visual field, negative light state); a second flash.	Reversal of colours; the previously central sensation of colour is now peripheral, the peripheral central.	In contrast with the previous blue, a reddish-yellow tinge appears for the intrinsic light of the retina, with darkening of the field of vision.	Reversal of closing effect = bright blue centre, yellowish-green ring. Brenner could only detect the blue centre with certainty.
After opening.	Permanent negativity of light. Gradual abolition of all visual phenomena.			

State of Current.	Ritter.	Purkinje.	Helmholtz.	Brenner.
II. Kathode to the Eye=Descending Direction of Current				
Closure of circuit.	Obscuring of visual field (negative light state). Flash. Red colour.	Reversal of preceding (anodic closure) phenomena. Illumination of visual axis; obscurity of optic disc; entrance of optic nerve a dark circular spot, surrounded by a clear violet ring; a bright violet quadrant at the visual axis. Here the light violet entirely covers the fundus, the yellow light, even at high intensities of current, being only like a trace of a weak gloss, or a yellow sap-colour on a dark ground.	The field of vision, which is illuminated only with the intrinsic light of the retina, is usually more obscure than before, and somewhat reddish-yellow in colour. The optic disc alone describes a bright blue circle upon the dark fundus. That half of the disc which is turned towards the centre of the visual field is alone, as a rule, visible.	Centre of disc bright blue; peripheral ring yellowish-green.
During closure.	Persistent negativity of state. Red colour.	...	...	The previous condition lasts some time and then grows fainter; at last disappears entirely. The central phenomenon again outlasts the peripheral.
Opening of circuit.	Cessation of negativity, and transition to positive state. Flash. Blue colour.	...	Visual field is again illuminated and bluish-white. Optic disc is obscured.	Reversal of former effects. Bright blue illumination of periphery, well-marked yellowish-green disc in the centre.

With very strong currents Helmholtz found "a confusion of colours," in which no rule could be discovered.

"The electrical excitation may also be confined to individual parts of the retina, although it cannot be sharply localised. The essentials of these manifestations have already been described by Purkinje. Helmholtz made one conductor out of a thin cylinder of sponge fully saturated with saline and tightly bound to a copper rod with an insulating handle. The other electrode was placed on the neck or grasped in the left hand, while the sponge made contact with the skin near the external or internal angle of the eye, which can be moved to and fro under the closed eyelids. When the sponge is positive electrode, the current passes on the proximal side of the eye into and through the retina, leaving it again on the distal side; the reverse occurs when the sponge is negative.

"The side of the retina at which current enters will then appear more obscure than the half by which the current leaves it, which is relatively brighter. It is to be remembered that these sensations are always referred by the subject to the opposite half of the field of vision, as if the electrical brightness were due to external illumination. The same rules hold good for the phenomena that occur when the electrode is placed anteriorly upon the cornea, covered by the eyelid. The positive electrode then gives current from within outwards, through the entire retina, producing the sensation of brightness." Helmholtz invariably found that the optic disc exhibited a contrary effect from that of the surrounding field.

"If positive electricity enters at the temporal side of the eye, the current passes from without into the peripheral portion of the retina, *i.e.* from cones to ganglion-cells, producing obscurity. But in the fibres of the yellow spot that are directed towards the temporal side, the current passes from ganglion-cells to cones, and produces brightness. The several effects may be summed up as follows: *A constant electrical current through the retina from cones to corresponding ganglion-cells gives a sensation of darkness, the opposite direction of current a sensation of light.*"

This, even more plainly than in the organ of taste, shows the antagonism of sensations with opposite directions of current in the same end-organ of the optic nerve. Any interpretation other than dissimilar action at the two poles is hardly conceivable.

It is obvious that we cannot speak of any regular passage of current in a given direction in the terminal apparatus of the *auditory nerve.* Brenner (27), to whom we owe the most extensive researches in this subject, placed one (the indifferent) electrode at any part as far removed as possible from the ear (back of head, chest, hand), while the other, with which he experimented, was introduced as a fine wire into the auditory meatus, after filling this with water, or applied as a small knob covered with moist flannel to the skin near the meatus.

If the kathode is used for the exploring electrode, a sound will be heard on closing a constant current of medium strength, which gradually dies away during closure; opening the circuit gives no auditory sensation. On the other hand, if the anode is applied to the ear there is no effect at closure, while the opening is accompanied by a sensation of sound, which is usually weaker than that at closure of the opposite current. On reversal from anode to kathode, auditory sensations are produced with an intensity of current at which a simple kathodic closure gives no reaction (voltaic alternative). Oscillations of current, starting not from zero, but from any finite value, produce the same auditory sensations.

In character the galvanic auditory sensation is for the most part in successful experiments, with not too strong currents, a true musical sound. Kiesselbach (49) determined its pitch as that of the intrinsic tone of his ear. Since this is also the pitch of the subjective sound heard with the so-called singing in the ear, Rosenthal (*l.c.*) assumes that "on simultaneously exciting all the auditory fibres with a weak stimulus, the resulting tone is always that to which the subject is, as it were, most accustomed."

As regards electrical stimulation of *cutaneous sensory nerves* many opinions have prevailed from the time of Ritter, the most prominent fact being that an ascending current produces warmth during its closure, while a descending current gives a cold sensation. With a zinc-copper pile of 150 couples, the poles of which terminated in beakers of salt solution into which the hands dipped, du Bois-Reymond experienced "waves of heat, and cold shudders, alternately, running up the arms to the shoulders." He was unable to convince himself that one arm felt heat and the other cold. Goldscheider (49), on the other hand, with even

twelve cells, experienced a feeling of warmth in the arm connected with the anode, but could not detect cold in the other arm.

VII. Polar Excitation by Currents of very short Duration (Induction Currents)

It has already been repeatedly pointed out that it is necessary, in order that current should produce electrical activity in excitable substances, that it should pass for a certain period, varying in absolute value within a wide range, according to the nature of the excitable tissue. This is especially true of the break excitation by the constant current, which implies, besides adequate intensity, a due period of closure, since the anelectrotonic state (*i.e.* the anodic alterations of current with the disappearance of which it is connected) can only develop fully under these conditions. Here, with indirect stimulation of the muscle, there can be no doubt that the development of an adequate anelectrotonus in the nerve itself requires such an interval: on the other hand, there are cases in which it may be asked whether the inefficacy of a make stimulus with brief currents is due to some property of the nerve, or of its peripheral end-organ (muscle). If, *e.g.*, a single impact of current, or induction shock, is effective when applied to the nerve of a cross-striated muscle, and ineffective when it acts upon the motor fibres of smooth muscle, it may be conjectured that the absence of contraction in the last case derives solely from the muscle, *i.e.* that the excitation passing along the nerve may be of the same nature and magnitude as in the first case, but that it is inadequate, or in some way inept, to stimulate the more sluggish tissues. Internal variations in the nerve must also be reckoned as factors.

However this may be, the manifestations of the law of contraction undergo considerable modifications with brief currents, even where the most rapidly reacting preparations are employed. Pflüger's law of contraction would lead us to anticipate that very brief currents effect no opening twitch, and this is supported by experiment. We have already seen that induction currents (which should theoretically produce a double excitation, since they are equal at make and break) act in striated muscle, at moderate intensity, from the kathode only; and within a

certain range of strength of current the same is undoubtedly true of indirect excitation of the muscle also. On the other hand, we know that stronger induction currents, acting upon curarised muscle, produce changes at the point of entrance (anode) also, which, if not invariably expressed in visible changes of form, cannot be interpreted otherwise than as the consequences of a break excitation. To this category belong more especially the *positive anodic polarisation currents* which appear as the after-effect of excitation by single induction shocks. In nerve, as in muscle, it may be shown by any of the above methods for proving the polar action of the constant current, that both impacts of current and single induction shocks excite within a certain range of intensity at the kathode only, *i.e.* that the twitches thus discharged must be defined as closure twitches. At Fick's suggestion, Lamansky (50) undertook experiments to determine (by v. Bezold's method, as applied to the constant current) the difference of latent period, with ascending and descending induction currents, at the seat of stimulation. The latent period was found longer for the ascending than for the descending direction of current. V. Vintschgau (51) next ascertained that with maximal, or nearly maximal, induction currents this difference of latent period is considerably greater than on exciting with weak currents. He is inclined to refer this to differences of spatial extension, and relative intensity of the electrotonic changes in the nerve produced by current.

The polar action of induced currents is also manifested in the different effects of excitation, according to the direction of current, in medullated nerve,—excitability being depressed in the region of the central electrode (Biedermann, 30). The facts relating to this point were already known to Harless, who found, on applying ammonia to a portion of the intrapolar region of the nerve, "that even the intrinsically stronger break shock had no effect after the action of ammonia, if applied to the nerve, at its former strength, in the ascending direction," while the make shock sent through the nerve in the opposite direction is effective. With uniform distance of coil there is never excitation when, with ascending direction of current, the kathodic section is rendered inexcitable by ammonia or any similar reagent, *i.e.* the excitatory process can only proceed from the kathode. We learn from the same fact that kathodic

excitation alone is discharged by induced currents of a certain intensity. Analogous experiments to those with frogs' nerves can easily be demonstrated on warm-blooded nerves, immediately after division without previous injury.

If two unpolarisable electrodes are applied respectively to the fresh cross-section, and to a point lying about 1 cm. below on the rabbit's sciatic, it will be found on exciting with single induction shocks of moderate strength that a twitch is discharged only when the current is descending in the nerve. Under certain conditions this striking reaction has a methodic value also, for it is clear that when any section of the nerve, within which approximately equal excitability may be predicated at every point, is excited with alternating currents, each single make as well as break shock must take effect at a certain distance of coil. This is no longer the case on stimulating the cut end of a warm-blooded nerve. Only the descending direction of current will then discharge an excitation, *i.e.* according to the direction of the primary current, the break shock or make shock only. With greater distance of coil, however, when the break induction current is eventually alone effective, excitatory action can only be expected when the current traverses the nerve in a descending direction. With uniform position of electrodes and distance of coil there will thus in the one case be a visible effect of excitation, in the other complete absence of effect, according to the direction of the primary current. And when Fick (52) observed that the action of an induction shock can only be augmented when its kathode, and not when its anode falls in the katelectrotonic region of a polarising constant current, this must be viewed as direct evidence of the polar kathodic action of induced currents. It was formerly supposed by Pflüger that the total excitability of the intrapolar tract could be measured by sending an induction shock through it during the passage of the constant current; but this could only be correct under the presumption that the induction current excited the whole tract simultaneously. Pflüger always made the induction current in the same direction as the polarising current, and therefore tested excitability each time at the kathode (which coincided with the kathode of the induced current); his conclusion, that weak polarising currents strengthen the effect of the (homodromous) induction current, while stronger currents diminish or abolish it, must therefore be interpreted like the

analogous data for direct excitation of the muscle. These experiments also show that mere *variations* of current density in the nerve (as also in the muscle) may excite equally with the rise or fall of the current from or to zero (make or break of the circuit). Later on, O. Nasse (53), Hermann (53), du Bois-Reymond (53), and others attacked the question of how far the absolute height of previously existing polar alterations affects the discharge of a twitch from the muscle, in sudden variations of intensity in the ("electrotonic") changes of the nerve that occur during closure at the kathode, after opening at the anode. Nasse showed (by a fall apparatus which closed or opened an incremental current, derived through a rheochord) a positive or negative variation of intensity superposed upon the existing battery current. The positive variation of descending currents was found to be increased with weak constant currents, to be diminished with stronger currents, while the negative variation of ascending currents was depressed at all strengths of the constant current. Hermann sums up the result of his investigations, on the Eckhardt-Pflüger method, in the dictum that the effect of a given induction current is raised (as in muscle) by homodromous constant currents (provided these do not exceed a certain range of intensity), and depressed (to abolition) by opposite currents. Since, as Hermann concludes, increase of a homodromous current is equivalent to closure of a homodromous or opening of a heterodromous current, while its sudden diminution corresponds with closure of an opposite or opening of a homodromous current (so that in the former case the seat of excitation coincides with a pre-existing katelectrotonus, but otherwise with previous anelectrotonus), the experimental results of indirect, as of direct, excitation of the muscle seem to be intelligible from the same standpoint.

If the exclusively kathodic excitation is thus to be regarded as ascertained for weak induced currents, we must, on the other hand, concede the probability that with *strong* currents even brief duration may develop an electrotonus adequate to produce excitation in the descending portion also. This is indicated in certain observations of Fick, Lamansky, and others. These refer, in the first place, to a characteristic feature of the height of twitch, in indirect excitation of the muscle with very brief constant currents (current impacts), on changing the intensity, duration, and direction of the latter. Fick determined (*supra*)

that there is at every intensity of current a minimum direction below which it cannot fall without abolishing the contraction; while, if the duration of the current increases beyond this limit, the twitch rises steadily from zero, and gradually reaches the maximum possible at that strength of current. The time-values involved are very low in excitation of the nerve. A duration of 0·002 sec. is the maximum. Fick finds that *the increase of twitch does not proceed constantly with increasing duration of a current of uniform strength descending in the nerve, but that the rise is intermittent: the twitches increase again after an initial maximum, if the passage of the current is prolonged.*

If, *e.g.*, a descending current of given strength discharges a maximal twitch with a closure of 0·003–0·004 sec., this will not increase with further increase of current intensity, provided the current continues to pass for a very short time only. But if the same current is persistently closed, a twitch results which is considerably in excess of the ultimate maximum from the momentary action of current, *i.e.* is in a certain sense a *supramaximal* contraction. This can only mean that the kathodic make excitation exhibits the greatest possible maximum in consequence of the prolonged passage of the current, as is expressed in both direct and indirect excitation of the muscle by the fact that no induction shock, however energetic, can effect the same degree of contraction as the closure of even a moderate constant current. Single induction shocks never elicit more than the relative maximum, that is not exceeded in brief constant currents also (Fick, *l.c.* p. 25). Between these extremes of brief impact of current, and persistent closure, it is quite possible that the irregular increase in height of twitch with increasing closure depends partly upon an anodic break excitation, since the effects of the closure and immediately succeeding opening excitation are summated in the muscle. In favour of this interpretation we have in the first place the fact that (as Fick discovered later) the same phenomena appear with descending induction currents, of increasing intensity, since after reaching a first maximum the twitches rise again to a second.

Along with these data we have the still more weighty observations of Fick (54). He found that with ascending impacts of constant currents the twitches declined after the first maximum to zero (the so-called "breach," *Lücke*), so soon as

the passage of the current, which remained at uniform strength throughout the experiment, exceeded a certain value. If the experiment was then continued with increasing duration of current, the twitches reappeared and rose to a second maximum, from which point they remained constant with further extension of stimulation. The same effect appears when the strength of the shock is varied with unaltered duration of current; further, with diminishing values of current duration the diminution and disappearance of the twitches implies increasing strength of current (Tigerstedt, 54, p. 4). Fick subsequently determined the same effect with ascending induction currents, since here too, with increasing intensity, there is a "breach" after the first maximum, followed by renewed twitches with further increase of current intensity, which soon become "supramaximal." The existence of the breach was confirmed by Tiegel (55), and again by Grützner (55). Tiegel claims to have seen it with both ascending and descending currents. Grützner, like Tigerstedt, on the other hand, failed to discover it with descending induction currents. The effect is quite regular with ascending induction currents. The twitches—beginning at a given, and under uniform conditions of experiment fairly constant, strength of current (distance of coil)—diminish rapidly, and then gradually rise again. The diminution in height with increasing strength of current occasionally fails to reach the zero, so that here the breach is, as it were, imperfect. As regards its interpretation, the breach must, according to Fick, be viewed as a result of inhibition at the positive pole, which at a certain strength (duration) of current is sufficient to neutralise the excitation proceeding from the negative pole. The character of the twitches appearing after the breach will be discussed later. The diminution and abolition of the twitches with an ascending shock, or induction current, would thus be perfectly analogous with the corresponding phenomena of the ascending constant current (Fick, 55). Grützner's theory, according to which the breach is to be referred to a sort of interference between pre-existing differences of potential between nerve current and exciting current, was finally disproved by Tigerstedt. The strongest evidence in favour of Fick's view is the fact that the breach only appears with ascending direction of current; if the inhibition at the kathode is not strong enough to neutralise the kathodic excita-

tion completely, there is merely a diminution in height of the twitches. In currents of brief duration the inhibition has not time to develop adequately and produce a breach; unless, at all events, the currents employed are excessively strong. This is doubtless the reason that the breach is not produced as readily with break as with make induction currents (Tigerstedt, 54), at least in cases in which the primary circuit is fully opened.

If we accept Fick's explanation of the cause of the breach, the reappearance of the twitches, and their rise above the initial maximum ("supramaximal contractions"), demand a special interpretation, more particularly when the effects of ascending excitation with the constant current is compared with that of single induction shocks, from the point of view of Pflüger's law of contraction. In the former, the make twitch never reappears after the third stage, whatever the augmentation of current intensity, the break excitation alone being effective. Presumably the twitches which appear beyond the breach on stimulating with ascending impacts, or with single ascending induction currents, may be viewed as *break twitches.* These, as we have said, begin to increase again after the breach, and with protracted rise of stimulus may gradually reach the same height as before. In some cases, but not always, the twitches rise with increased strength of current beyond the first maximum, and reach a considerably greater height (*i.e.* are "supramaximal"); Tigerstedt (*l.c.* p. 22) has shown that when supramaximal twitches do not appear even with the coils pushed home, it is quite easy to call them out if the nerve is further excited with uniform direction of current at the same rhythm. Whether this is due to a kind of summation of effects, or to other changes in the nerve produced by current, must for the moment be left undetermined. It is easy to see that the appearance of supramaximal twitches with brief descending currents, as described above, can be interpreted on the same principle. On the theory of Fick we have here only summation of the excitations produced by the rise and fall of current. With descending currents we know that excitation proceeds from the pole proximal to the muscle. On its passage to the muscle it therefore encounters no inhibition, and arrives with undiminished strength. But when a (break) excitation starts from the positive pole of the induction current, it has a longer course than the make excitation, and reaches

the muscle perceptibly later. Let the make excitation be maximal; if the twitch which it induces begins in the muscle before the terminal excitation arrives there, summation of the two twitches must ensue—there is "supramaximal" contraction. The time-relations of the two curves harmonise with this conclusion.

Fick found, in the course of an experiment on the latent period of twitches with increasing intensity of current, that the first (considerably reduced) contraction after the breach showed "an enormous prolongation of latent excitation." This cannot be due to diminished strength of stimulation immediately after the breach, for, even when the twitches after considerably exceed those antecedent to it, the latency in the former is measurably greater than in the latter. This sharp distinction between the twitches before and after the breach determines them not to be perfectly homogeneous. It has been pointed out by Waller (56) that the latency of break twitches with the constant current is much greater than that of the make twitches, and Biedermann confirms this fact. If the twitches after the breach, as well as those which bridge it with falling strength of current, really correspond with the break twitches of the constant current, we should *a priori* expect them to exhibit the same characteristics in regard to the latent period.

Summing up the previous data, it may be stated with great probability that—"The twitches before the breach are discharged by the impact of an induction current (shock); these have a brief latent period; the twitches after the breach, as well as the twitches which bridge it with diminishing intensity of stimulus, are caused by the disappearance of the brief current. These, like all opening twitches, have a long latent period in comparison with the closure contraction. When, with falling strength of current, the point is reached at which the inhibition at the positive pole can no longer hinder the transmission of the excitation to the muscle, the short latency (suddenly) reasserts itself" (Tigerstedt).

If certain "supramaximal" twitches thus depend upon summation of the anodic and kathodic excitation, we may expect to demonstrate the same by separating the two stimuli so far in time that the interval should be at least as great as the latent period of the contraction. This, according to Fick and Lamansky, could

be accomplished by lengthening the intrapolar region. In order to obtain the necessary interval between kathodic and anodic stimulation, the intrapolar tract must, however, be at least 150 mm., conductivity being reckoned at 30 m., and the latent period at 0·005 sec. It is not possible to produce summation of muscular contraction by this means with induction currents in frog-preparations (Mareš, 57). On the other hand, the method of time-measurements still further supports the assumed bipolar excitation from strong induction currents. If, *i.e.*, the excitation occurs at one pole only—the kathode—the latent period of the muscle-twitch must (as is indeed well established) be longer with ascending than with descending direction of current, and that proportionately with the time occupied by rate of transmission in the intrapolar region. If, on the contrary, excitation takes place at *both* poles, the latency with both directions of current is equal, and corresponds with the excitation from the pole proximal to the muscle. This presumption was experimentally verified by Mareš (*l.c.*).

VIII. Effect of Repetition of Stimulus

No matter what conception we adopt of the nature of the excitatory process, it is always interesting to see in any appropriate terminal organ the effect of several simultaneous or successive stimuli at different points of the nerve. We have already referred to the case of bipolar excitation by induced or constant currents, but still greater interest attaches to the action of *simultaneous* stimuli. *A priori* it is, as Hermann points out, most probable that the two independent processes of excitation travel undisturbed over the nerve, at an interval corresponding with the distance between the two points of stimulation, and arrive successively at the terminal organ. The resulting effects must depend solely upon the nature of the end-organ. In muscle, *e.g.*, the second stimulus would, according to the interval, be ineffective, or would cause a superposed twitch, or a second independent twitch. Even when two excitations meet in the same fibre, an undisturbed passage in either direction is conceivable; and such an encounter must, in fact, take place in every simultaneous stimulation of two points of a nerve, since the upper excitation cannot reach the muscle without crossing the lower impulse, which, of course,

travels up as well as downwards (Hermann, 34, p. 109). All observations hitherto made on this point refer exclusively to experiments with two electrical stimuli. The results of this method, which have been variously diagnosed as summation, or as interference effects, are by no means free from ambiguity. In using electrical stimuli, *i.e.*, we must take into consideration not merely the combination of two independent processes of excitation,

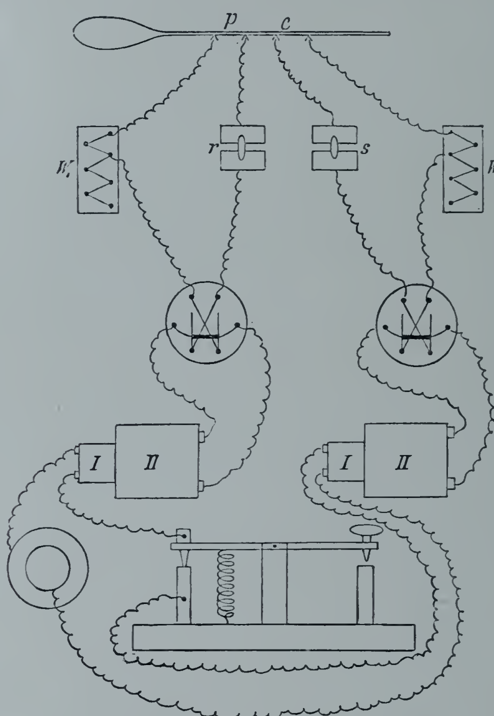


FIG. 200.—Schema for simultaneous excitation of a nerve by induction shocks at different points. (Werigo.)

but also (owing to the nature of the electrical stimulus) alterations in the conductivity of the nerve, which are unfavourable to the integrity of the experiment.

Grünhagen (58), in order to obtain the absolutely simultaneous action of two or more distinct currents upon different points of a nerve, devised the method of leading the current from a sufficiently strong battery through two or more primary induction coils, with as many corresponding secondary coils. Every closure

or opening of the battery circuit will then discharge absolutely simultaneous induction currents in all the secondary coils, and these can be led off to points of the nerve by means of unpolarisable electrodes. The method is shown in the accompanying diagram (Fig. 200) from Werigo (58).

Four combinations are possible, relatively to the direction of the two exciting currents. These may either be homodromous (ascending or descending), or, with opposite direction, may flow to or from each other, so that with the first the kathodes, with the second the anodes, are in juxtaposition. If current intensity is so adjusted that one current in itself gives minimal, the other no contraction, both shocks being in the ascending direction, a reciprocal effect appears; *i.e.*, with not too great a distance between the exciting electrodes, the ascending stimulus directed towards the muscle (peripheral), and of itself inadequate (inframinimal), perceptibly augments the action of the central, ascending current, while conversely a central, ascending, inframinimal stimulus inhibits the already minimal effect of an ascending, peripheral current. If both induction currents are descending, the same effects as in peripheral, inframinimal excitation hold good of the central, and *vice versa*. If the currents flow towards each other, the final effect is that of mutual augmentation, until a maximal twitch may arise from two stimuli, each *per se* ineffective; while with not undue distance between the excited parts an antagonistic inhibition may be detected.

These results coincide with those of Sewall (58), and are easily reduced to the polar action of the current. "Augmentation will invariably be found on applying the exciting current in the vicinity of the kathode of the modifying current, with the converse diminution when it is sent in near the anode." Always, however, the increase of excitability in the katelectrotonic region is more strongly marked than its diminution in that of anelectrotonus. If both shocks are effective, even if unequally, the distance between the two excited parts being such that electrotonic effects are absolutely excluded, the muscle reacts to the stronger excitation only—and that as if this alone were present. There would thus seem to be no real interference in the sense of addition or subtraction of stimuli. If the distance between the excited parts is reduced, the effects become much

more complicated (owing to the interference of electrotonic alterations of excitability) than when *one* shock only is acting; since both the modification of the central current by the peripheral and that of the peripheral by the central then come into play. In such cases, all the resulting phenomena are in line with the laws of electrotonus.

Kaiser (59) has recently described a special case of interference between two excitations discharged at different points of a nerve. He found, *i.e.* with simultaneous excitation of the frog's sciatic at two points as far apart as possible, on the one hand by tetanising alternating currents, on the other by glycerin, that the glycerin tetanus was sometimes inhibited at the beginning of and during the electrical stimulation. Since the same effect appears in the simultaneous action of two different chemical stimuli (glycerin and NaCl, or glycerin at both points), explanation by electrotonic alterations of excitability is *ab initio* excluded. When the same chemical stimulus acts upon two distinct points of the nerve, there is at most a very moderate tetanus, the sudden strengthening of which after amputating the upper seat of excitation is very striking. It seems tolerably certain that the inhibition that occurs in nerve-fibres, subjected simultaneously at two distinct points to tetanising stimuli, is due to processes which run their course in the nerve itself. Since the negative variation (as shown by the capillary electrometer) is invariably augmented under these conditions, instead of diminishing, as might *a priori* be expected, there cannot be merely an interference effect of the electrical waves of variation in the nerve, in the physical sense that they are neutralised by the coincidence of unequal phases. According to Kaiser, there must, whenever an excitatory wave is overtaken and submerged by the following wave, be "summation of negativity in the coincident points," so that in the given case "the waves of excitation resulting from the two stimuli are more or less fused together, and the amplitude of the variation sinks below the limen required to evoke action from the muscle."

We already know from innumerable examples that simple summation of excitatory conditions may occur at any point of the nerve, inasmuch as the excitability of any part of the nerve appears to be heightened when it is the seat of a weak and intrinsically inadequate (latent) excitation.

IX. Unipolar Excitation

Under certain conditions, excitation with induced currents brings to light phenomena which are not merely of theoretical interest, but have great practical value in all experimental observations. Among these is the so-called unipolar excitation by induction, first noted and worked out by du Bois-Reymond (*l.c.* p. 423). The facts underlying the entire subject are as follows: "If the nerve of a rheoscopic leg is connected with one end of an *open* induction circuit, either the leg or the other terminal of the circuit being led off to earth, a twitch occurs each time that an excitatory process is set up near the circuit, sufficient to have produced a secondary current in the circuit if it had been closed" (*l.c.* p. 429). This occurs even with complete insulation of the preparation, and also, at a given (short) distance of the coils, when there is no lead-off to earth (by touching the preparation, or connecting the other free pole with the ground). The excitation fails when the metallic end of the induction circuit is led off by contact above or below the point on which the nerve rests, or when, with the nerve hanging freely, contact is made with the preparation, and the muscles are led off by touching them. In the first case, ligaturing or crushing the nerve does not inhibit the excitation, seeing that the nerve is traversed by electricity in its entire length, inclusive of the crushed part. Pflüger (2, pp. 57, 121, 410) found that break shocks were markedly the most effective—explained by du Bois-Reymond as due to delay in charging the secondary coil, by the development of the extra current.

In order to produce unipolar excitation, it is not necessary to lead off from one pole to an infinite conductor (such as the earth). The effect on the contrary appears, as first pointed out by Pflüger (*l.c.* p. 128 f.), even when the led-off pole is in contact with a comparatively small surface, the more so in proportion as the P.D. arising from the E.M.F. due to induction is higher. "The degree of unipolar action increases rapidly with the magnitude of the lead-off, unipolar stimulation being greater at any given point, with a restricted leading-off surface, in proportion as this point lies nearer the seat of unipolar action at the metal pole." Pflüger placed a row of frogs' legs (4-6) upon a glass plate, after insulating all the apparatus as carefully as possible, so that only the nerve of the first touched the (single) metal pole, that of the

second the foot of the first, that of the third the foot of the second, and so on. Gradual approximation of the coils of the induction apparatus caused each leg to twitch in succession. This shows that "unipolar action in the vicinity of the metal pole is a fallacy likely to occur even with scrupulous insulation."

Under certain conditions the effect of "induction" is very beneficial to unipolar excitation. Du Bois-Reymond had occasionally observed, when the finger was brought closer to a nerve-muscle preparation attached only to one pole, that twitches appeared which were not otherwise present at the same strength of current. This—as found by F. W. Zahn (60)—is the case not merely when the free end of the circuit is led off by contact with the other hand, but even without this. Zahn modified this experiment in many ways. He placed the preparation upon a round glass plate, the under surface of which was covered with tinfoil to within 10 cm. from the edge. On connecting one pole with the leg, the other with the sheet of tin, tetanus appeared even with weak currents. The same thing occurs with rather stronger currents when the limb is disconnected from the secondary coil, at the moment of leading off by contact, or when the free metal pole is grasped in one hand while the other is brought near the preparation. The experiment is still more successful if the glass plate is evenly covered on both sides with metal, turning it into a Franklin's Board. If one sheet is then connected with one pole, the other with the nerve of the preparation, while the leg hangs over the non-metallic glass edge and makes contact with the other free pole, so that the circuit is interrupted only by the glass disc between the two sheets of tinfoil, twitching and tetanus are set up with even weak currents. The result is the same on connecting one end of the induction circuit with the lower sheet, while the other terminates in a plate of tinfoil brought close to the leg. With the coils pushed home, there is also stimulation when one end of the circuit is left free and isolated, on bringing a plate of tinfoil sufficiently near to the limb.

Tiegel (60) connected one pole of an induction apparatus with a gas-pipe, while the other terminated in an isolated metal plate which could be moved towards a corresponding plate standing opposite to it. The latter was in circuit with a glass plate covered with tinfoil, on which the preparation was lying. Each

time the muscle-nerve was touched there was excitation, varying in strength with the distance between the plates, and susceptible with a suitable lead-off (by a fine metal point) of very exact localisation. In this case also, the break shocks only took effect. Schiff and Fuchs (60) also obtained unipolar action *without induction,* with the exclusive action of static electricity. They carried the charges from the ends of an open circuit into a large conductor, or the plates of a condenser, and then led them through an excitable nerve. The following experiment by Rosenthal (60) is also suggestive. A nerve-muscle preparation insulated on a glass plate, upon which the nerve and muscle lie in a trough, is suddenly brought near a charged conductor, held by an insulated glass handle, on which a small twitch may occur when the end of the nerve is proximal to the conductor,—never, on the other hand, when the conductor is brought near the muscle end. But if in the last case the nerve is led off by contact, or even connected with an insulated conductor of any size, there is always marked excitation.

The theory of unipolar excitation, of which we have thus been considering some instructive instances, was essentially developed by du Bois-Reymond, who showed that it depended upon the electrical potential at the two free ends of an induction coil. At the moment of opening or closing the primary circuit, an open secondary circuit represents, as it were, an open battery, with free electricity at its two ends. If each pole of the secondary coil is connected respectively with the nerve of a frog's leg, *both* preparations twitch if one of them is led off to earth—because both nerves are traversed by the flowing electricity, in opposite directions. The same thing of course takes place when only one metal pole is connected with the nerve of a preparation, the lead-off being either from the leg or from the other free pole. The electricity necessary to charge the leg always flows through the nerve, and thus excites it. Obviously, the intensity of the excitation depends in first degree upon the amount of electricity flowing through the nerve—increasing accordingly with difference of potential, approximation of coils, and lead-off from free pole. Augmentation of the electrical capacity of the leg produces the same result. To this is due the favourable effect of connecting up a unipolar preparation with conductors of a larger surface (human body, etc.), as well as the approxima-

tion of a neutral body, or better, of a conductor containing the opposite charge, from the other end of the coil (= *induction*).

When, as in the above experiment from Tiegel, one pole of the secondary coil is led off to earth, there must at the moment of induction be a certain (positive or negative) charge (potential) at the metal plate connected with the other pole, which must be twice as great as it would be if the other pole were not led off. The effect of induction upon the second insulated metal plate, parallel to the first, is to set up a potential of the opposite sign which varies with the distance. At the next moment, the negative electricity (let us say) of the charged pole flows through the secondary coil to the other pole, and the positive electricity of the plate charged by induction flows through the nerve-muscle preparation to earth, whereby excitation is produced.

The unipolar effects that occasionally appear (as was again pointed out by du Bois-Reymond) with incomplete closure of the circuit are of great practical importance in all electrical experiments with induced currents. If the nerve of a frog's leg is laid across two electrodes connected with the poles of a secondary coil, so as to close the induction circuit, a ligature being then applied to the myopolar tract, tetanus may still be observed in the isolated leg, on making the lead-off from it at a certain distance of coil. It is evident that the same would occur if the nerve were cut away above the crushed and no longer conducting point, and replaced by any moist conductor. Here, as in all the previous experiments with an open circuit, the direction of the unipolar passage of the current makes itself apparent, in accordance with the law of contraction. Excitation occurs only with charges in which positive electricity leaves, or negative electricity enters, the nerve. These unipolar effects may obviously be very disturbing, and are indeed productive of fallacies in vivisection, and also in experiments with the galvanometer, if not avoided by due precautions. Hering (61) has pointed out that in experiments such as the investigation of the negative variation of nerve currents, in which galvanometers and exciting circuits are separated by a long tract of nerve, the most complete insulation of the two circuits is no guarantee against the overflow of induced electricity through the interpolar part of the nerve into the galvanometer circuit.

There must always be, along with the short-circuiting through

the interpolar tract, a flowing off in the complex of conductors which forms the galvanometer circuit, and which must (however well insulated) be connected through the nerve with the secondary coil. Hering further showed by special experiments that the sudden charges and discharges in the galvanometer circuit, caused under all conditions by the interpolar flow of electricity, do not as a rule produce any deflection of the magnet.

The following experiment demonstrates plainly in what degree the connection of the nerve with the galvanometer circuit is responsible for unipolar excitation. "A sciatic nerve, still in connection with the leg, was laid across the exciting and galvanometer electrodes just as in the determination of the negative variation (exciting tract = 5 mm., intermediate tract = 25–30 mm., galvanometer tract = 6–8 mm.). The stump of the thigh-bone was fixed in a paraffin clamp with a corresponding bore, so that the leg is as far as possible insulated. After repeated crushing of the intermediate tract, the preparation was stimulated, and the secondary coil gradually pushed up. Unipolar action began at 20–25 cm. distance of coil, and the muscle went into tetanus even if one galvanometer electrode only was in contact with the nerve. On taking both galvanometer electrodes off the nerve, the muscle remained quiescent" (Hering). The difference between this and ordinary unipolar excitation is that electricity here does not flow over to the muscle, but passes through the galvanometer electrodes into the galvanometer circuit, and thereby excites the nerve, partly below the crushed point, partly at the seat of the galvanometer electrodes (more particularly at the long section).

This kind of unipolar stimulation is an obvious danger in all experiments on action currents and negative variation in nerve, while it shows what narrow bounds restrict the intensities of current that may be safely used in these experiments.

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CHAPTER X

ELECTROMOTIVE ACTION IN NERVE

I. Current of "Resting" Nerve

Du Bois-Reymond communicated his first observations on galvanic action in the divided nerve in 1843, after many vain attempts on the part of Matteucci and others to demonstrate its existence. A complete historical account of all the preliminary researches may be had in the second volume of du Bois-Reymond's classical work. Modern methods have facilitated the recognition of the "law of the nerve current" in each excised particle of cold- or warm-blooded nerve—which law, apart from differences of intensity in the resulting effects, coincides in every particular with that of the muscle current. In both cases, each point of the natural, uninjured surface (the "natural longitudinal section") is positive to all points of an "artificial transverse section"; in both the difference of potential is greatest when the "equator" is connected with the cross-section by the leading-off circuit, such P.D. being greater or less according as the points of the long section are less positive to the cross-section, *i.e.* are more closely approximated to it; each point nearer the equator being also positive to each more distant point (weak longitudinal current). As in muscle, we must assume each single nerve-fibre to be equally electromotive with the entire nerve-trunk.

Du Bois-Reymond determined the absolute E.M.F. of the nerve current as 0·022 Dan. in frog, 0·026 Dan. in rabbit. The following table from Frédéricq (1) shows the E.M.F. of medullated nerve in the frog to be much the same as in various warm-blooded animals, while the nerves that are composed of non-medullated fibres in both vertebrates and invertebrates are characterised

by a striking preponderance of electromotive force (Kühne and Steiner, 2):—

Cat	0·018 Dan.
Dog	0·018–0·021 Dan.
Rabbit	0·020–0·028 Dan.
Duck	0·024 Dan.
Lobster	0·048 Dan.

In the non-medullated olfactory nerve of the pike, which is of approximate diameter with the frog's sciatic, Kühne and Steiner found an E.M.F. of 0·0215–0·0105 Dan., while in the frog's sciatic it was only 0·002–0·006 Dan. In any case these figures show the E.M.F. of the non-medullated olfactory nerve of pike to be greatly in excess of that in medullated frog's nerves. The difference is more than half. The medullated optic nerve of the pike, which has a far larger diameter than the olfactorius, alone approaches the lowest figure (0·0100 Dan.) given for the latter. The cause of this striking difference between medullated and non-medullated nerve is, according to Kühne, "either that the specific E.M.F. is greater in non-medullated than in medullated nerve, or that the medulla of medullated nerve is *per se* electrically inactive, electromotive force being confined to the axis-cylinder; so that similar cross-sections of medullated and non-medullated nerve would not correspond in electromotive condition, and medullated nerve would only exhibit the same electromotive force as non-medullated nerve, when its anatomical cross-section exceeded that of the latter to the extent occupied by the medulla in the section" (Kühne and Steiner, *l.c.* p. 160).

The electrical reaction of the slender, non-medullated connective nerves of *Anodonta* (3) also points to the conclusion that the electromotive activity of medullated nerve-fibre derives from the axis-cylinder only, without participation of the medulla. These nerves, under favourable conditions, yield very strong currents—as also the mantle nerves of *Eledone,* in which the E.M.F. amounts, according to S. Fuchs (4), to 0·0259 Dan., though they are frequently of smaller diameter than the sciatic nerves of large Transylvanian frogs. Gotch and Horsley (5) find a striking difference of potential between longitudinal and artificial transverse sections in the spinal roots of mammals. While the E.M.F. of the demarcation current of mixed mammalian nerve is 0·01 Dan. in cat, 0·005 Dan. only in monkey, it amounts in the posterior spinal roots of the cat to 0·025 Dan., and even

in the spinal cord to 0·046 Dan., and 0·029 Dan. in monkey. Comparison of the spinal cord of young full-grown animals with the large nerve of adults proves that this is not due solely to the greater sectional area.

In all experiments upon the so-called current of rest in the nerve (Hermann's "demarcation current"), it is essential that the lead-off from the cross-section should be as clean as possible. It is, of course, more difficult to lead off from the transverse section of finer nerves than from coarse trunks. Hence it becomes advisable to destroy a certain tract near the transverse section, and to lead off from the dead end. Under conditions in which the demarcation current of the frog's sciatic yields at most a galvanometer deflection of about 70 degrees, Biedermann obtained deflections of 60–200 degrees from the two juxtaposed nerves of mollusca, the diameter being still considerably below that of a single frog's nerve. In non-medullated nerve also there is *a zone of rapidly diminishing negativity* near the demarcation surface, which again produces "weak longitudinal currents" (Biedermann, *supra*, also Kühne and Steiner).

The reaction of nerves that are different in function is very striking on leading off from two cross-sections, when the current should be zero, if the negativity on both sides were equal. This is not, however, the case (du Bois-Reymond, 6): a difference of potential occurs not merely in the frog's sciatic, but also in the nerves of warm-blooded animals (Frédéricq, 1, p. 68, note).

Mendelssohn (6) subsequently found regular and apparently constant differences of negativity between any two cross-sections in pure centripetal or centrifugal nerves. Du Bois-Reymond had already in electrical nerves shown greater negativity of the peripheral cross-section as compared with the "equator," so that the current from section to section, the so-called "axial current," is always in an ascending direction. The same is true, according to Mendelssohn, of the (purely centrifugal) muscular branches of the rabbit's sciatic; while in the posterior roots of frog and rabbit, as also in the optic and olfactory nerves of the fish, the axial current is descending. In the mixed trunk of the sciatic, again, the direction is alternating. If any law could be formulated from these observations, it would be that the axial nerve current is opposed in direction to the physiological action of the nerve fibres. These observations may conceivably be brought into line

with the data cited above for differences of excitability, and susceptibility to injury, at different points of the uninjured nerve. Mendelssohn convinced himself that the E.M.F. of the axial current was greater in proportion with the rate at which the excitatory impulses traversed the nerve in one or the other direction, *i.e.* the more the nerve was excited within the organism.

The great regularity of electromotive action in divided or otherwise injured nerve obviously goes no further towards establishing the pre-existence of an electrical potential within such tissues than in the parallel case of muscle. Here, as there, on the contrary, it must be affirmed that the perfectly uninjured nerve is electrically inactive. It is obvious, in view of the mode in which the nerve-fibres end in the peripheral organs, or central system, that we cannot speak of leading off from a "natural cross-section" (in the same sense as in muscle), especially as not merely the motor end-organs (muscle), but others (*e.g.* gland-cells) also, are proved to be, actually or potentially, the seat of electromotive action. This applies, *inter alia*, to the organ which seems at first sight best adapted to decide this question, viz. the *eye*, as investigated by du Bois-Reymond and others. Some account of its electromotive activity will be given below.

Electromotive action in nerve, as in muscle, is a vital property of the living tissues. The nerves of a corpse gradually (albeit in most vertebrata very slowly) cease to exhibit any difference of potential between a fresh demarcation surface and points on the uninjured superficies. It is intelligible that this should occur sooner in warm- than in cold-blooded animals, as also that nerves left in the body should preserve their normal properties longer than excised nerves; and that excitability should decline most rapidly in the central tracts that are, generally speaking, the least capable of resistance. Steiner (7) finds that the E.M.F. of the nerve current increases within a certain range with rising temperature, reaching its maximum between 14° and 25° C. At boiling-point the current is reversed, according to du Bois-Reymond, as Harless also finds at a certain stage of drying. Electromotive activity may persist for a long time during the process of degeneration suffered by nerves that have been separated from their centres, which is also natural, seeing that the medullary sheath is first to be disintegrated in medullated fibres. Schiff and Valentin (8) found that nerves of birds and mammals,

when divided in the living animal, exhibited a normal current weeks and months afterwards, although excitability disappeared 8–14 days after the operation. Schiff asserts that the axis-cylinder was still present, in spite of advanced disintegration of the medullary sheath,—a further proof of the physiological significance of this portion of the fibre.

The alterations in time suffered by the demarcation current in medullated nerve are of extreme interest, since they are analogous with those of cardiac and smooth muscle. Engelmann (9) found that the E.M.F. of the cross-section fell with extreme rapidity, and appeared again in undiminished vigour when a new section was made. This he explained from the fact that the individual cells die separately, notwithstanding their physiological coherence—the process of death is confined to the cells that are directly injured. Similar relations appear in medullated nerve-fibres, although these cannot be regarded as consisting of separate cells fused together. After only 1–2 hours Engelmann noted that the E.M.F. of the artificial cross-section fell from 60 to 25 per cent of the initial value, in 20–24 hours to at least 35·5 per cent, more often to 0; frequently, as pointed out above, there was a weak reversed current. Renewal of the cross-section in every case restored the full value of the original current.

Head (10) found, on repeating Engelmann's experiment, that the diminution of the demarcation current was especially marked in the nerves of summer frogs, so that the increase of E.M.F. in consequence of the new cross-section is here particularly striking. After 14 minutes the very pronounced current of rest was observed by Head to fall to $\frac{1}{5}$ of its original value. Twenty-eight minutes after beginning the experiment a new section was made, upon which the nerve current at once reappeared in its former vigour. As a rule, there was even a marked rise of E.M.F. beyond the original magnitude. In one special case the current of rest in a frog's sciatic gave a deflection of 155 degrees, which fell 20 minutes later to 32 degrees of the scale. After making a new section, the current at once increased to 120 degrees, and, after a second rapid fall, gave a deflection of 232 (!) degrees, on applying another (fourth) cross-section, 33 minutes after beginning the experiment. Engelmann explains this striking reaction from the fact that the process of mortification in the injured fibres is arrested at the nearest node of Ranvier. The same effect appears,

however, in the optic nerve of the fish (Kühne, 9), where the fibres have no constrictions, and also in non-medullated nerve (Biedermann, 3), although in a less marked degree, so that there is no adequate reason for assuming definite anatomical boundaries within the continuity of the axis-cylinder, at which the process of mortification shall be arrested. If the fact that the separate cell-individuals in cardiac and smooth muscle are directly united by plasma-bridges is of universal application, the consequences of renewing the section can only indicate that the death-process is arrested at some distance from the cut surface, without confining it within preordained anatomical barriers.

Nerve, like muscle, can be excited by its own demarcation current. The facts relating to this subject have been familiar since the days

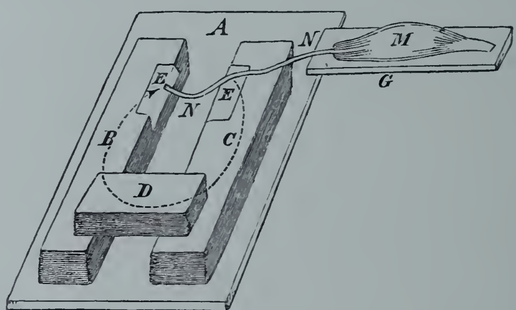


FIG. 201.—Excitation of nerve by its own current.

of Galvani, and have more especially been investigated by Kühne and Hering (11). Galvani introduced the nerve of a rheoscopic leg into an open circuit, and allowed the nerve of another leg, completely isolated from the first, to fall upon the circuit, in such a way that the cross-section of the first nerve formed one of the two points of contact. Both legs twitch in a successful experiment. Du Bois-Reymond laid the central end (transverse and longitudinal sections) of a sciatic nerve, still connected with the leg, across the pads of his zinc trough-electrodes, making and breaking the nerve current by means of a mercury key. "The leg twitched at closure and at opening, in some cases on breaking the circuit only." Du Bois-Reymond subsequently simplified this experiment by placing two long pads of filter-paper saturated with salt solution close together upon an insulating stage, and laying across them the long and transverse sections of the rheoscopic nerve.

The circuit was closed by applying a third pad quickly, whereupon the muscle contracted (Fig. 201). The point here being adequate rapidity of closure and opening, the two pads on which the nerve is resting may hang freely over the edge of a glass plate, a vessel of salt solution being rapidly raised or lowered below them (Hering, *l.c.*), or two blocks of salt clay can be employed, which are readily moulded into any form (Kühne, *l.c.*). The twitches resulting from this last method are, as Kühne showed, most energetic. In excitable preparations Hering obtained vigorous make and break twitches, when the tract of nerve between the clay blocks was lengthened to 1 cm. This gave reason to anticipate that a nerve may be tetanised by its own current as well as by the interruptions of a battery current. With this object, Kühne employed a vibrating mercury key; Hering, on the other hand, constructed a special apparatus, by which he obtained a "tetanus without metals." "The rapid raising and dropping of the closure pad (*supra*) was effected by the teeth of a rotating cog-wheel, which lifted the one-armed lever, and the closure-pad attached to its free end, while a spring fastened to the lever drew it down again after each rise." "The simplest means of exciting a nerve by its own current is, as remarked by Hering (*l.c.* p. 241), to let its end fall upon a second *isoelectric* moist conductor." Metals (platinum, amalgamated zinc) are less suitable for this purpose, because they very shortly set up polarising currents. "If the end of the nerve falls upon a drop of lymph, blood-serum, or weak salt solution, the effect usually occurs once only, because the fluid that clings to the nerve when it is lifted out again short-circuits it permanently and effectively. But if the nerve falls upon a coagulated drop of blood, or a block of clay saturated with 0·6 per cent NaCl, the experiment may be freely repeated." An isoelectric muscle will obviously be a convenient sub-stage for the same purpose. "If a nerve still connected with the leg is allowed to fall upon the gastrocnemius muscle, the resulting twitch is no proof that the nerve is excited by a muscle current, although this may generally be the case." Czermak pointed out that frogs' legs of great excitability will contract when their nerves fall upon portions of the intestine, kidneys, or liver of a rabbit, which no more proves the preexistence of a P.D. in those parts than the observation of Donders that frogs' legs may twitch under certain conditions, when the

cut end of the nerve drops upon the pericardium during diastole (cf. Kühne, *l.c.* p. 85).

A twitch is often produced, as in muscle, by merely bringing the cross-section of the nerve into contact with a drop of conducting fluid. Eckhardt (12) employed this last method to investigate chemical stimulation of nerve, as Kühne had done for muscle. For both we must distinguish between the electrical excitation caused by short-circuiting of the demarcation current, and the resulting *chemical* action—a difficult if not impossible task in many cases. The electrical origin of the twitch which (as Hering noted) makes its appearance on touching a fresh cross-section with a drop of 0·6 per cent salt solution, or of the concentrated solution of zinc and copper sulphate, said by Eckhardt to be chemically inactive, can hardly be disputed. With the very active solutions of fixed alkalies, on the other hand, where we must take into consideration that the magnitude of the twitch may be due solely to the fact "that they moisten the nerve more rapidly and efficaciously than other fluids, and thus produce a quicker electrical variation in the nerve," the same cannot be asserted with equal certainty. In all experiments on excitation of nerve and muscle by their intrinsic currents, great excitability of the preparation is, as has been stated, indispensable; hence they come off best in the cold season. In experimenting on frogs' nerves that have been kept in a cold room (at about 0° C.), Hering has again pointed out the extraordinary tendency to tetanic excitation exhibited under these circumstances—particularly by *R. esculenta*, in a less degree by *R. temporaria*. The simple division or constriction of the sciatic is, as a rule, sufficient to induce a protracted, unbroken spasm of the leg, which is on an average the more marked as the nerve is divided higher up, and may be called out again after it has expired, by making a fresh cross-section.

Since these very excitable preparations fall, under the action of the weakest battery currents, into a "closure tetanus" that lasts during the entire passage of the current, it is not surprising that, under such conditions, the mere short-circuiting of the demarcation current will cause tetanic excitation — as was frequently observed by Hering. Vigorous closure twitches, with or without subsequent clonic disturbance, occur not merely on bringing a fresh cross-section of the sciatic nerve into contact

with the nearest accessible point of the longitudinal surface, but also when the cut end drops upon that of a second nerve. In the last case, however, contraction occurs only when the two cut ends are not in the same line, but the one nerve falls longways upon the other, so that the two ends come together. There is thus mutual reaction of the two demarcation currents, since they flow in the same direction through the circuit formed by the two cut ends. (Hering previously performed the same experiments successfully with two curarised frogs' muscles—sartorius). "The fact that sufficiently vigorous nerves fall into persistent excitation when their own current is short-circuited externally, leads us to conjecture that the above-mentioned tetanic excitation, as seen in cooled frogs after dividing the nerve of the leg, or the sciatic plexus, may also be caused solely by the current incident upon such division"; since the sheaths of the single fibres, and the common neural integument, alike provide an internal path for the individual currents of the fibres.

The above facts refer to motor frogs' nerves only. It was, however, shown by Knoll (13) that centripetal nerves of warm-blooded animals can also, under certain conditions, be excited by their own currents. These experiments refer exclusively to the cervical vagus of dog and rabbit, and more particularly again to the central portion, which is in connection with the respiratory centre. The mere exposure of these nerves, especially where they are injured, causes protracted expiration, or even a brief expiratory pause in respiration, in the rabbit; while similar effects of longer duration appear with great regularity on raising a cervical vagus, ligatured at the thoracic end and isolated, from the wound, or lifting it out of an indifferent conducting fluid, especially when the nerve has previously been divided peripherally to the ligature (cf. Langendorff, 13). A more or less prolonged expiratory pause is again produced on dropping the vagus on the wound, or moistening it with a conducting fluid (0·6 % NaCl). Since it can be shown in all these cases that neither mechanical, thermal, nor chemical stimuli come into play, and since "all the factors known to produce a nerve current react favourably upon the experiment as described above,"—respiration further remaining unaltered "when uniformity of other conditions has prevented the setting-up or reinforcement of

a short-circuit,"—it cannot be doubted that these expiratory effects are due to excitation of the expiratory fibres of the cervical vagus, by some variation in the intrinsic nerve current. Obviously, when the nerve is raised from, or dropped on to, the wound in the neck, there must be complication from the currents of the injured muscles. Knoll also refers the brief expiratory effect which usually appears after simple division or constriction of the vagi *in situ*, to excitation of the nerve by its own current, and this effect must certainly be regarded as the analogue of tetanus from division of the sciatic nerve in a cooled frog. It should be noticed that the peripheral end of the vagus cannot be stimulated to action, *i.e.* retardation of the cardiac beat, by its own current.

The marked E.M.F. of the non-medullated olfactory nerve of the pike explains the fact that its current readily and invariably excites frog nerves. If looped over the end of a glass rod, it may be dropped on to any point of a frog's nerve, forming a fine pair of electrodes, and never fails to produce vigorous twitches in the leg if contact is made at the transverse and longitudinal sections (Kühne, 11, p. 97). Kühne even succeeded in exciting curarised frogs' sartorii by the demarcation current of the pike's olfactorius.

Much interest, especially in regard to the theory of the break twitch, attaches to the phenomena of interference between the nerve current and an artificial current, when the exciting electrodes are applied to the proximity of a cross-section, or to any point along the nerve that happens to be electrically active. Pflüger pointed out that the excitability of a tract of nerve must be positively affected by its own current when a transverse section is made, or a lateral branch of the nerve amputated above the tract, since the demarcation current throws that part of the nerve into katelectrotonus. If a leading-off circuit connects the transverse section, or a proximal point on the longitudinal surface, with any other point of the latter, current passes through the part of the nerve between the contacts from transverse to longitudinal section. Seeing that the separate axis cylinders are, like the entire nerve-trunk, surrounded by indifferent conducting sheaths, there must (apart from the special conditions in medullated nerve) be lines of current within the sheaths in the same direction, making their exit at different points of the surface of the single fibres, as of the entire nerve,

in the part near the transverse section (as was pointed out more particularly by Hermann). If the leading-off electrodes serve at the same time for excitation, *i.e.* if they lead an artificial current into the nerve, this will either be homodromous or heterodromous with the current already present in the entire system, —the former when the anode is proximal to the cross-section. Other conditions being uniform, the closure of a current homodromous with the intrinsic current increases the excitation, so that it is intelligible that a descending current in the vicinity of the cross-section should prove more effective than an ascending current. In view of the previous argument, it is clear that the interference effects between exciting current and nerve current are due, strictly speaking, not to addition and subtraction of these currents (Grünhagen remarks that an exciting current increased or diminished by the sum of the nerve current exhibits no appreciable alteration of its physiological action), but to polarisation effects discharged at points at which the disposition to response has been altered in one direction or the other by the internal neutralisation of the nerve current.

If actively electromotive (negative) points occur in the continuity of the undivided nerve, the same considerations of course apply to them. Grützner (14), indeed, inclines to refer all changes of excitability in the continuity of the otherwise uninjured nerve (in particular the dissimilarity of action with equal but opposite currents in different parts of the same nerve, as described by Hermann and Fleischl) to differences of potential induced by preparation.

If a frog's sciatic is tested with unpolarisable electrodes 5–8 mm. apart, there is regularly, according to Grützner, a descending current below the point at which the branch to the thigh is given off, an ascending current, on the contrary, above the gastrocnemius. About midway between pelvis and knee there is a point at which no current can be led off to the galvanometer (Fleischl's “ equator ”). There is no doubt that the P.D. is caused by the side branches given off from the main stem. When these are as far as possible uninjured, the currents are very weak. Each point of bifurcation in the nerve is thus, as it were, predestined for the appearance of a P.D., since it presents a suitable point of attack to injuries of all kinds.

“ Wherever the intrinsic currents of the nerve are descending,

excitation is best effected by a descending current, and *vice versa*. If, on the contrary, the nerve current and exciting currents are heterodromous, the action of the exciting current will be diminished or abolished" (Grützner, *l.c.*). Fleischl (15) subsequently tried to overthrow this interpretation on the ground that effects corresponding to his "law of contraction" might also be observed in nerves of which the P.D. was compensated by an artificial current. This, however, was answered by Grützner and Hermann, who pointed out that compensation can only neutralise the branch of the current that flows in the applied circuit, and not the internal P.D. of the nerve (or muscle), with its corresponding currents.

A remarkable case of interference between nerve and muscle currents is that cited by Hering (11), in which the tetanus consequent on division (*supra*) is absent, even in preparations from highly susceptible cooled frogs, on dividing the thigh with a single cut, when the current from the divided muscle, ascending in the nerve, acts upon the latter so as to neutralise its current.

As in striated muscle (sartorius) denervated by curare, "spurious break twitches" may result from interference between demarcation current and artificial exciting current,—so likewise in nerve. The striking dependence of the opening excitation upon the proximity of the anode to an artificial section of the nerve has already been insisted on. It is highly probable, if not proven, that these opening twitches from the cross-section are not true opening twitches, but closure contractions from the nerve current previously compensated in the leading-off circuit—*i.e.* that this effect is wholly analogous with the "false opening twitches of injured muscle" (Hering, Grützner, 11).

If a rheochord is employed to send a branch of the current from a battery through a nerve resting by its transverse and longitudinal sections upon unpolarisable electrodes, the closure or opening of the circuit being effected by a key introduced between rheochord and electrodes, there may in favourable cases (Hering, 11) be a contraction, both on closing and on opening the "nerve circuit" (which short-circuits the demarcation current externally), even when the rheochord is not in the circuit. If this is effected, and a key introduced, together with a reverser, into the same ("battery") circuit, the excitatory effects must differ (when the deriving current from the battery is ascending in the nerve, and

therefore compensates the demarcation current at a sufficient intensity) according as, with previous closure of the nerve circuit, the battery circuit is made, or with closed battery current the nerve circuit is completed. The "apparent" closure twitch that appears in the former case alone must, properly speaking, be an opening effect of the nerve current, as, on the other hand, the "false" break twitch discharged after previous closure of both circuits, by the opening of the key in the battery circuit, must be a closing effect of the nerve current, as indicated by its absence when the nerve circuit alone is opened. "If the branch current from the battery is too weak to compensate the nerve current in the nerve circuit, it will still have some effect in the same direction, though not in the same degree. If, on the other hand, it is stronger than is necessary for compensation, the current in the nerve, after closure of both circuits, will actually be ascending, although it is only, as it were, traversed by the remainder of the branch from the battery current. If the nerve circuit therefore be closed, with previous closure of the battery circuit, there will be no contraction, provided the branch current from the battery be not too strong. If, on the other hand, the battery circuit be made with previous closure of the nerve circuit, the opening effect of the nerve current is superposed upon the weak and intrinsically inadequate closing effect of the battery current, and a contraction is obtained."

"If the nerve circuit is opened with previous closure of the battery circuit, there is no twitch, provided always that the ascending battery current in the nerve is not so powerful as to excite opening twitches — notwithstanding its partial compensation by the nerve current. If, on the other hand, the battery circuit is opened with closed nerve circuit, the nerve current simultaneously finds a new short-circuit, and contraction follows, which is here still further augmented by the action of the voltaic alternative" (Hering, 11).

Accordingly, "on commencing operations with the weakest *outgoing* branches of the battery current, as they find exit at the transverse section of the nerve, the break twitch makes its first appearance on opening the battery circuit, and only with much stronger currents at break of the nerve circuit also. The 'make twitch,' again, is first seen on closing the battery circuit, and only with stronger deriving currents at closure of the nerve circuit also."

If the battery current *enters* at the transverse section of the nerve, *i.e.* is descending, the effect, as pointed out by Hering, is again dissimilar, according as the battery circuit is closed with previous closure of the nerve circuit, or *vice versa*. "For in the former case a current, viz. that of the nerve, is already entering at the longitudinal electrode, so that the superposition of the branch from the battery current will only increase it. But if the nerve circuit is closed subsequent to closure of the battery circuit, the nerve current and battery current will summate at the moment of closure, and the effect of the latter is thus augmented. At break of the nerve circuit, again, the two currents disappear simultaneously." "On commencing with minimal ingoing currents at the cross-section of the nerve, the make twitch appears first at closure of the nerve circuit, and only with stronger currents on closing the battery circuit also. An analogous reaction may be determined for the opening twitches" (Hering, 11).

Du Bois-Reymond (*Ges. Abhandl.* i. p. 196) pointed out that, under certain conditions, the effect is fundamentally different according as the current is made or broken in the principal or deriving circuit (battery or nerve circuit). But as metal electrodes were exclusively employed in these experiments, there must have been extensive external polarisation at the interface of the animal tissues and the electrodes.

A characteristic effect of interference between exciting and nerve current is the "breach" in the series of opening twitches, first pointed out by Grützner (14). It may be observed when any part of the nerve, in which there is a descending current (as, *e.g.*, at the cross-section), is excited with ascending battery currents of increasing strength. Opening twitches then appear even with very low intensities of current, increasing at first with its augmentation, and then diminishing to zero, after which they again increase in magnitude.

The magnitude, *i.e.* E.M.F., of the current in a leading-off circuit, in which one contact is applied to the transverse section of a nerve, while the other rests upon a point of the longitudinal surface, of course depends to a large extent upon the distance between the electrodes. The deriving current is experimentally found to be greatest when this = 5 – 7 mm., when compensation by an artificial heterodromous current will accordingly be most adequate. The conditions are much less favourable with

a less distance between the exciting (or leading-off) electrodes. Accordingly the breach in the series of opening twitches is much plainer in the first case than in the second (Ludmilla Nemerowsky, 16). Grützner (*l.c.*) proposes to explain the phenomenon as follows :—"The exciting current may be less than, equal to, or greater than the nerve current. In the first case the nerve current will diminish at closure of the exciting current, and when the latter is opened will return to its original height. When the exciting current is equal to the nerve current, the nerve current (in the deriving circuit) sinks to zero at closure of the exciting current. On opening the latter the nerve current returns from zero to its original height. Lastly, where the exciting current is stronger than the nerve current, its closure sends into the nerve a current less than, and opposite in direction to, the nerve current. At break, on the contrary, this reduced exciting current disappears, and the nerve current rises again from zero in the momentarily isoelectric nerve." According to Grützner, an exciting current weaker than the nerve current—as well as one that is stronger—excites when the circuit is opened. In the first case the excitation is discharged at a point which has been rendered considerably more excitable by the kathode of the intrinsic current; in the second, on the other hand, the action of the voltaic alternative comes into play, since a current traverses the nerve shortly after the passage of a heterodromous current. The disappearance of a current just sufficient to compensate does not excite, because the current which rises from zero does not find exit at any especially excitable point. This coincides with the fact that the "breach" in the opening twitches never appears at isoelectric points of the nerve, unless these have been polarised by the previous passage of stronger currents. In such cases the breach reappears, if exciting currents are employed which are heterodromous to the polarising current passing through the nerve.

Lastly, we must reckon among the phenomena of interference between nerve current and artificial exciting current the characteristic reaction which (as first investigated by Hering, 11) appears in nerves that are stimulated with induction currents in the proximity of the cross-section. "If the electrodes from the secondary coil of an induction apparatus are placed at a distance of only 2–3 mm. upon the freshly divided or ligatured nerve, in

such a manner that one rests upon the transverse section, or point of ligature, even minimal currents will produce a very marked effect, when the opening current in the nerve is abterminal (*i.e.* parallel with the nerve current). With atterminal direction of current, on the contrary, the effect—albeit with uniform position of electrodes and strength of current—is very much weaker, or fails altogether. If with an abterminal opening current the electrodes are removed farther and farther from the cross-section, the effect of the current declines quickly, and finally vanishes altogether. If, on the other hand, the opening current is atterminal, its action on moving the electrodes away from the cross-section increases rapidly, attains its maximum, and then subsides with further shifting, until it disappears entirely."

II. Electromotive Changes produced by Electrical Excitation (Current of Action)

The state of activity in nerve-fibres is not characterised by any directly visible alterations in the nerve, so that in order to recognise it the nerve must be left connected with its muscle or other peripheral organ. This acts as indicator for the nerve, since neither optic, nor chemical, nor any other demonstrable alterations can be recognised in the nerve itself. In its electromotive reaction, however, du Bois-Reymond perceived a means of detecting the state of activity by means of the nerve itself. Immediately after discovering the nerve current, du Bois-Reymond found in the year 1843 that it *diminished during tetanus*—*i.e.* underwent a "*negative variation*," the signs of which agree essentially with those of the negative variation of the muscle current. Du Bois-Reymond showed that, as in the latter, the effect is the expression of an altered state of the nerve, and not of any experimental errors whatsoever. Apart from other facts to be mentioned below, this is more particularly seen in the circumstance that the negative variation can be observed with even very weak alternating induction currents, quite independent of the length of tract between the leading-off and exciting electrodes in the nerve; so that it essentially depends upon a diminution of E.M.F., concomitant with the state of tetanic excitation in the divided nerve. The extent of the negative variation,

measured by the resulting swing of the galvanometer magnet, is proportional at all points of the nerve to the strength of the original demarcation current, and is therefore maximal on leading off from the cross-section and most positive point of the longitudinal surface, *nil* on leading off from two isoelectric points. Even with a maximal negative variation, it can be seen directly with an aperiodic galvanometer that the diminution of the nerve current during tetanic excitation never amounts to complete abolition, so that a greater or less fraction of E.M.F. remains constant. The negative variation of the demarcation current is, as we should *a priori* anticipate, the same in non-medullated as in medullated nerve.

In the olfactory nerve of the pike it was found by Kühne and Steiner to be very vigorous, which agrees with the high E.M.F. of the "current of rest." Since non-medullated nerve, like muscle, reacts better to stimuli of prolonged duration than to short induction shocks, the negative variation is perceptibly stronger when the tetanising excitation is effected by the rapid make and break of a constant current. This is more especially the case (as tested on molluscan nerve—Biedermann, 3) when the unfavourable effects of a current flowing in one direction are eliminated by introducing a rotating reverser, or by quickly turning a Pohl's commutator. At the close of the rhythmical excitation the magnet usually returns with decreasing rapidity to its position of rest, or there may in stale preparations be a negative remainder of the deflection. On attempting to tetanise molluscan nerve in the ordinary way by means of a du Bois' sliding inductorium, and thus to obtain a negative variation of the demarcation current, there is usually complete absence of effect, under the most favourable relations of excitability, even when the coils are pushed close together. This minimal activity of brief currents is also very marked with interrupted constant currents, where the magnitude of the negative variation does not usually increase (as in medullated nerve under similar conditions) with increasing frequency of stimulation, but on the contrary undergoes a diminution, which is the more considerable in proportion as the interruptions of the current are more rapid, *i.e.* as each single stimulus is shorter. Since a similar reaction may be observed in the electrical excitation of the non-medullated claw-nerves of crayfish, this must be a widespread property of non-medullated

nerve, which thus stands in the same relation to medullated fibres as smooth to striated muscle. In agreement with this, the single closure (eventually the opening also) of a constant current produces as a rule a marked negative variation of the demarcation current, an effect that occurs in medullated frog's nerve only under special conditions (Biedermann, 3).

Let the two connective nerves of *Anodonta* be prepared together, with leading-off electrodes at the cross-section (after killing one end), and at a point of the longitudinal surface some 6 mm. higher up, while unpolarisable electrodes are simultaneously applied to the other end of the pair of nerves (which are moderately stretched between two supports), these electrodes being connected by means of a reverser with 1–2 Dan. cells. There will, then, at each closure of the exciting circuit, after compensation of the demarcation current, be a more or less marked deflection of the magnet in the direction of decrease, or negative variation, of the nerve current, the magnitude of which is essentially dependent upon the direction of the exciting current. If the latter flows towards the end led off (which may be termed descending), the action is invariably much stronger than with the opposite direction. Careful investigation of this phenomenon leaves no doubt that it arises from the consequences of exciting the nerve by the constant current, *i.e.* is a negative variation in the true sense of the word. This is shown not merely by the independence of the direction of the deflection from that of the current, but also by the time-distribution of the effect, and the relations exhibited between strength and direction of exciting current on the one hand, and magnitude of effect on the galvanometer upon the other.

As regards, first, the distribution of the negative variation. With descending direction of current this usually occurs so that the deflection seems to begin at the moment of closure, or imperceptibly later, reaches its maximum with tolerable rapidity, and then, the current being still closed, declines rapidly at first and afterwards more slowly. If the circuit is opened during this period there is sometimes a marked delay in the backward process, or even a reinforcement of the negative deflection. In most cases, however, the opening has no effect, or there may even be a *positive after-variation*, which with prolonged closure of the exciting current may develop while the current is passing. This

deflection—*i.e.* increase of the nerve current, to which we shall return below—is either (as in the majority of cases) smaller than, or equal to, or even larger than the previous negative variation. Its appearance seems to accompany the most favourable conditions of excitability in the nerve, from which we can understand how there comes often to be a distinct positive after-effect with the first excitations, that subsequently fails altogether. As regards dependence of these excitation effects upon strength of current, it must be stated that visible effects upon the galvanometer appear first at a comparatively marked intensity of the exciting current, and always in the first place with the descending direction. These rapidly increase in magnitude, and attain a maximum that is not exceeded with any subsequent increase of the descending current, while the negative variation at closure of the ascending direction, on the contrary, declines, and even fails altogether when the current is increased beyond a certain point. And as ascending closure inevitably produces a weaker negative variation of the demarcation current, its subsidence is invariably more rapid than after the closure of a descending current. If the exciting tract is remote from the led-off galvanometer tract, the magnet usually returns to its position of rest even while the current is passing. With less distance between the two, there are, on the contrary, very striking effects (*infra*), which have nothing to do with the excitatory manifestations we are here discussing.

The dissimilar action of descending or ascending currents is again characteristic at break of the exciting circuit. While a negative "opening variation" rarely appears distinctly with descending direction of current, it may with the ascending direction be equal to, or larger than, the initial deflection at closure of the exciting circuit, which then, as a rule, recedes considerably, or even fails altogether. With tolerably strong ascending currents, and a longer distance between leading-off and exciting tracts, the negative opening variation is, as a rule, the sole effect of stimulation.

It is evident from these data that there are simple and regular relations between the magnitude of negative variation induced by closing or opening an adequate battery current, and the intensity, direction, and duration of the latter, proving immediately that we are in presence of the consequences of make and break excitation.

At closure of both descending and ascending currents there is often a considerable diminution of E.M.F. between the longitudinal and transverse sections in the nerve, which is, however, much less, and continues for a shorter time, with the ascending direction. If the current remains closed for a sufficiently long period, the negative variation will either be entirely abolished in the course of a few seconds, or (with descending direction) there may be a remainder of negative variation, which only disappears—if at all—on opening the exciting circuit.

The magnitude of the negative variation is therefore almost independent of the distance between leading-off and exciting electrodes. It does not increase perceptibly when the intermediate tract is shortened, nor will it exceed a certain (easily attained) maximum on strengthening the descending exciting current. If the current, on the other hand, is ascending, the negative variation declines with its increasing intensity, and is finally abolished, exhibiting therefore, in this respect, a reaction precisely similar to that of the closing excitation with ascending direction of current. With respect, lastly, to the sequelæ of the break-effect, there is again complete uniformity between the reaction of the opening excitation (in so far as it is expressed on exciting the motor nerve by changes of form in the muscle) and the alterations of the demarcation current, as above. This is more especially true of the dependence of the negative opening variation upon the strength and duration of the ascending exciting current. It invariably appears first with a much higher intensity of current than that demanded by the closing effect, and increases in proportion with the duration of closure in the exciting circuit. Hence it is possible, with sufficiently prolonged closure, to produce a distinct negative opening variation, even with comparatively weak ascending currents. With descending battery currents there is seldom a pronounced negative variation at break; in most cases it is merely indicated by a transitory delay in the return of the scale. The most striking coincidence is that exhibited between the galvanic effects of excitation in non-medullated molluscan nerve, and the mechanical effects in an ordinary nerve-muscle preparation, on employing an electrical stimulus corresponding with the first or third stage of Pflüger's law of contraction. In the first of these two cases a negative variation (closing excitation) is apparent at closure of

both ascending and descending currents, while the opening of the exciting circuit has no visible effect. In the second the consequences are exactly opposite with the two directions of current, since a negative variation then appears only with closure of the descending and opening of the ascending current, while closure of ascending and opening of descending currents has no effect.

Further evidence of the causal relation between the galvanic effects in question, and the excitation of the nerve by current, is afforded in the fact that both are equally affected by killing the terminal portion of the exciting tract. We have already seen that in medullated and non-medullated nerve, as in striated and smooth muscle, the excitatory process is hindered, or altogether obstructed, when the current enters or leaves at a point that has been injured. And in fact, after killing a portion of the exciting tract (2–4 mm.), the negative variation at closure of the ascending current disappears almost as completely in molluscan nerve as does, in the other case, the closing excitation in the muscle. On the other hand, the negative variation is as little affected by the same injury at make of the descending current as by break in the ascending direction, thus showing that the first effect is caused by an alteration of the nerve deriving from the kathode, the second by alteration from the anode.

In medullated frog's nerve an analogous effect is apparently hindered only by the suppressed inclination to persistent excitation from the current flowing at constant density. Engelmann (17) long ago observed on nerves that were in the peculiar state in which every closure, or opening, of a battery current induces more or less sustained excitation (expressed in the muscle by closing or opening tetanus), that the galvanometer showed a corresponding negative variation of the demarcation current, on leading off from the transverse section.

In order to obtain this effect in its integrity on medullated nerve, *i.e.* undisturbed by other galvanic manifestations to be discussed below, it is advisable to take very sensitive preparations of cooled frogs, and to test at maximal distance between leading-off and exciting tracts, with the weakest possible currents. A distinct negative variation will then regularly appear below the kathode of a descending current, reaching its maximum at a low intensity of current, and being invariably more pronounced

than at closure of an ascending current. On the other hand, there is usually in this last case (as the galvanic expression of opening tetanus) a negative deflection, conditioned essentially by the duration of the previous passage of current, which declines very slowly.

We have already seen that the negative variation in non-medullated molluscan nerve is followed, under given circumstances, by a distinct *positive after-variation*—*i.e.* increase of the demarcation current. Hering (18) had previously observed the same effect in medullated frog's nerve during tetanus, where also the negative variation of the nerve current is generally followed by a positive variation that makes its appearance at the close of excitation, immediately subsequent to the negative variation. Thus du Bois-Reymond's statement that "the needle of the multiplier invariably returns to rest more or less imperfectly after tetanisation" (which he attributes to loss of E.M.F. in the nerve in consequence of the previous excitation) is, as Hering points out, inadequate.

The effect is most distinct when the nerve current has been previously compensated. "The negative variation is then expressed in the deflection of the magnet from its point of rest, in an opposite direction, by the now predominant compensation current. At close of excitation, however, the magnet does not merely return to its zero-point, but passes beyond it, and is then immediately, or shortly after, reversed, and slowly settles down at zero. This is the positive after-variation." Owing to its rapid subsidence, and to the sluggishness of the magnet, the effects are generally still stronger when the galvanometer circuit remains open during excitation, and is only closed immediately afterwards. "The positive after-effect increases up to a certain point with the duration of excitation. It is already visible when the stimulus lasts only a fraction of a second, and reaches considerable proportions after excitation for one second. The increment, as produced by duration of excitation, is only conspicuous in very brief periods of stimulation. It subsequently grows but little with an increased duration of stimulation, declines again when the excitation exceeds a certain limit, and disappears altogether with further prolongation" (Hering). Head (10), who studied the positive after-variation more closely under Hering's guidance, found that it increased within certain limits with intensity and duration of stimulation. Under favourable

conditions (more especially in preparations of cooled *Temporaria*) the positive deflection not infrequently exceeded the previous negative variation. In *R. esculenta*, according to Head, the average of maximal positive variations was something over 50 per cent that of the largest negative effects ; in *R. temporaria* it was over 81 per cent. In " warm " frogs kept for several days in a room where the temperature did not fall below 15° C. even at night, the positive after-variation invariably failed, in spite of a marked negative variation. This seems to be due to some alteration at the longitudinal lead-off, developed at the close of the stimulation, and opposed in its electrical relations to the effect of excitation. It may perhaps be regarded as the galvanic expression of some reaction of the excitable substance from the previous excitation (as negative variation upon the galvanometer), a process of restitution that only appears fully under favourable conditions.

From this point of view it is intelligible that the positive after-variation should increase within certain limits with the duration of the previous excitation, as also that with repeated stimulation the positive should decline before the negative effect. For the potential reaction in the nerve must be essentially reduced by persistent activity, supposing this to be accompanied by definite, even if minimal, metabolism. The " non-fatiguability " of medullated nerve proves this to occur only in the lowest possible, and not directly demonstrable, degree. The positive after-effect (or, more correctly, its absence) would accordingly be the only certain criterion of fatigue in nerve-substance. " The more or less exhausted nerve is characterised less by weakened response to excitation, than by failure to give the opposite reaction at the cessation of the stimulus, as energetically as the fresh nerve. The vigour of this reaction, as expressed in the positive (after) variation, is the measure of energy in the nerve " (Head).

In view of the extraordinary resistance of medullated nerve, whether cold- or warm-blooded, to the total interruption of its normal nutritive relations (*supra*), it is scarcely surprising that the negative variation should appear on the galvanometer as the expression of excitation (like the excitation itself in the normally-nourished and natural end-organ), long after the nerve has been isolated. Hermann (19) often observed galvanic manifestations of excitation in rabbit's nerves for several hours after the muscle had ceased to respond, and had indeed lost its

direct excitability. Frédéricq (1) observed a negative variation in the nerves of rabbit, dog, and horse, with electrical stimulation, up to 24 hours after death, and Boruttau (20) claims to have kept frogs' nerves for 7 to 12 days at low temperature without impairing their faculty of giving a distinct, though weak, negative variation when electrically excited. Lastly, Steinach (21) has observations to the effect that (recently) dried frogs' nerves yield a genuine negative variation again, if they are bathed in 0·6 % NaCl. Starting from certain purely physical effects on the so-called core-model (*infra*), Boruttau thence concludes that "the persistence of those properties in the nerve, by virtue of which its galvanic manifestations when at rest (demarcation current), and during electrical action (negative variation), are to be observed, must be referred less to the survival of that by which the nerve is still capable of discharging muscular activity, than to the conservation of its normal structure." In other words, "the galvanic effect known as the negative variation of current appears in the nerves of dead preparations also, when these are submitted to the same electrical stimulus that calls out muscular activity in fresh preparations." "Both mechanical stimuli (cutting, crushing) and chemical excitation" produce, according to Boruttau, a negative variation from "dead" frogs' nerves, 8 days old, on the capillary electrometer, and he finds the same result from the vago-sympathetic of the dog, on tetanising it mechanically 2 to 3 days after excision.

Granting the facts as stated in these observations, the conclusions can hardly be accepted. Unless absolute reason can be shown to the contrary, we are presumably justified under all circumstances in maintaining that the negative variation in nerve, as in muscle, is *the galvanic expression of excitation in living nerve —a vital physiological manifestation*—and not merely an "undulating (physical) katelectrotonus." No one accustomed to consider the excitatory manifestations of living matter from a general point of view can for an instant doubt that the negative variation is to be regarded as a special case of the action current, not merely in medullated, but also in non-medullated nerve, in smooth and in striated muscle; probably indeed in many other kinds of excitable protoplasm as the concomitant, and effect, of those chemical alterations which, properly speaking, constitute the process of excitation. Clearly we ought not to revive in "nerve

and muscle physics" (where it long enough blocked the way) the one-sided physical conception of vital phenomena so recently disproved in all departments of physiological investigation. There is, on the other hand, no sufficient reason for regarding the nerves on which Boruttau experimented as really dead, with no remainder of physiological excitability; as will be admitted by every one who has seen how even warm-blooded nerves (*e.g.* vagus), when divided, and completely isolated by lifting them out of the wound, so that they cannot be normally nourished, may be successfully excited many hours afterwards, provided only that the peripheral organ (heart, respiratory centre) be in good condition. Under all circumstances, the failure of indirect and even of direct muscular excitability in no way establishes the complete death of the nerve belonging to it, and, notwithstanding Boruttau's protest, we may still legitimately classify the action current, as well as the negative variation of all excitable tissues, under one category.

III. Electromotive Changes produced by Stimulation other than Electrical

The galvanometer, by recording the negative variation of the nerve, is thus (*supra*) a reliable indicator of the state of its excitability, without further reference to the alterations of the peripheral end-organ. It must be admitted to afford indubitable evidence of conductivity in both directions. If the peripheral end of a motor nerve is stimulated, a negative variation appears on leading off from the central cut end, and *vice versa.* Again, on exciting a purely centripetal (sensory) nerve, the negative variation may be demonstrated at any point peripheral to the seat of excitation. From this point of view it becomes essential to test the negative variation with excitation other than electrical. We are already familiar with the fact that nerves which are dissimilar in function do not react alike to identical stimuli, but exhibit marked differences. Grützner (22), *e.g.*, showed that centrifugal and centripetal nerves react quite differently to *thermal excitation*, the latter becoming, with few exceptions, highly excitable at a temperature of 40° to 50° C., while the former (with the exception of the vaso-dilators) do not seem to be excited. Strictly speaking, however, these

experiments prove nothing as to the processes that are taking place *within the nerve*, the conclusion being only formed retrospectively, from the reaction of the peripheral organ. If the motor apparatus exhibits activity when the nerve is stimulated by any means, there can of course be no doubt as to its excitation. Otherwise, however, there are two possible alternatives: either the nerve is not really excited, or at least the excitatory process is not transmitted; or the terminal apparatus may not react to the conducted stimulus (Grützner, *l.c.*).

If, then, the negative variation is a true expression of excitation in the nerve, it affords a simple and convenient means of testing the excitability of different nerves, independent of the end-organ, towards various stimuli. Here, again, there are two alternatives: (1) homogeneous stimuli, acting upon different nerves, may produce the same negative variation, and in this case the disparity of effect must be referred to the end-organ; (2) the negative variation itself may differ, in correspondence with the dissimilar effects of excitation in the end-organ. The cause of the heterogeneous effects must then lie within the nerve itself. From this point of view Grützner (22) in the first place investigated the effect of *thermal excitation* upon the negative variation in different nerves. A similar experiment, but one that is open to criticism, had been made by du Bois-Reymond (23). He placed the nerve (frog's sciatic) upon a layer of moist gunpowder, which, when lighted, charred the nerve from one end onwards. Notwithstanding the indisputably drastic stimulus to the successive sections of the nerve (which, by the way, can hardly be termed "thermal"), the galvanic consequences were very inconspicuous, and not to be compared with the marked effects of electrical excitation. Obviously, as was pointed out by Grützner, the negative variation may here be checked *ab initio* by the unavoidable shortening of the excitable portions of the nerve.

Yet, with a more perfect method, Grützner failed in obtaining any effective results. At temperatures of 40°–50° C. the demarcation current of frog nerves did indeed decline perceptibly, but only to an inconspicuous degree, and very slowly; there was, moreover, as a rule, a persistent diminution of the current, so that the effect was hardly comparable with that from electrical stimulation. Experiments on the anterior and posterior roots gave still less certain results, so that the question whether

thermal stimuli affect centripetal more than centrifugal nerves must therefore, as concerns the magnitude of the negative variation, remain undecided. Nor did Grützner elicit negative variation from *mechanical stimuli* (*e.g.* scissors-cut) at any distance from the seat of excitation. Only when the incision came within 10 mm. of the longitudinal electrode was there a slight, and that a permanent diminution of the current. On the other hand, in dividing the non-medullated olfactory nerve of the pike, Hering (24) found not merely a strong negative variation, but a distinct positive after-effect also, and analogous results are exhibited by non-medullated molluscan nerve (Biedermann). Steinach (21) has recently succeeded in proving that in suitable frogs' nerves (*e.g.* from cooled animals) each single cut will, under certain conditions, produce a marked negative variation, the time-distribution of which corresponds as a rule with that found in electrical stimulation. The mirror swings back rapidly, and reaches the point of rest again more slowly. This is obviously in line with the slow subsidence of the persistent excitation, as expressed in the inclination of a muscle to tetanus, when its nerve is excited by the constant current, or by short-circuiting of its own current. Boruttau (p. 31) also noted positive results in frog nerve with mechanical excitation, both with simple division and in mechanical tetanus.

With chemical excitation by NaCl, Grützner observed a gradual diminution of current, while Kühne and Steiner (2) obtained a negative variation of the demarcation current on the pike's non-medullated olfactory nerve, under the same conditions. Whether the poverty of effect is due solely to asynchronous excitation of the separate fibres of the nerve-trunk (Grützner), or to other factors also, is uncertain.

After cutting off the part of the nerve that had been excited, or bathing it in physiological saline, Steinach found that the diminution of the demarcation current due to chemical stimulation was completely neutralised. Alcohol proved the most effective excitant, and here again there was a marked difference between cooled and warmed frogs. With the former, immersion of the central end of the nerve produced tetanus of the flexors, succeeded by a vigorous extensor-tetanus, while, under similar conditions, a nerve-muscle preparation from a warmed frog gave only a few twitches, and was then quiescent.

The negative variation of the nerve current is under all circumstances a far less sensitive excitatory reagent than the reaction from the natural end-organ. Even in electrical excitation the visible reaction from the muscle appears earlier, *i.e.* at a greater distance of coil, than the negative deflection on the galvanometer. The requisite interval of current intensity is invariably much greater in warmed than in preparations of cooled frogs. Steinach excited both sciatic nerves simultaneously with induction currents, one nerve being connected with the leg, while he led off from the other to the galvanometer. In a warmed frog, tetanus first appeared with the coils 43 cm. apart, the negative variation at 27 cm.; in a cooled frog the distances were respectively 39 and 38 cm. Granting that these experiments are inconclusive as regards the presence of qualitative differences in the nerve-fibres, the fact that the negative variation is sometimes very weak, or altogether absent, in electrical stimulation, where all the fibres are simultaneously and equally excited, at least suggests this inference. Frédéricq (1) remarked upon the insignificance of the negative variation in electrical excitation of mammalian nerve, and Grützner has recently notified the same effect. No trace of negative variation can be obtained from an artificially-cooled rabbit, although the same excitation of the sciatic nerve causes a pronounced tetanus of the muscle. Apparently the alterations fundamental to the negative variation are in this case not transmitted, although the nerve as a whole is still excitable, and able to conduct, at all points. The negative variation may be observed in normal, uncooled, mammalian nerve, always, however, in a strikingly inferior degree from that of frogs' nerve. In this case a negative variation of 10 per cent of the nerve current is readily obtained with maximal currents, while the same stimulus only elicits a variation of 4 per cent in mammalian nerve.

In all these cases we have been concerned with excitation of the nerve in its continuity. *What, in the next place, is the negative variation on stimulating the natural end-organ (central or peripheral) of the nerve-fibre?* We are again indebted to du Bois-Reymond for the first observations on this point. In strychnia-spasm he observed a distinct diminution of the longitudinal-transverse current, on the frog's sciatic nerve still in connection with the spinal column. In the conviction that the

negative variation was to be regarded as the galvanic expression of excitation, du Bois-Reymond poisoned a conveniently arranged frog with strychnia, and then, after ligaturing the iliac artery on one side, divided the sciatic nerve of the same side at the knee, and exposed it as far as the vertebral column. He then led off to the multiplier from the peripheral end. If the strychnia-spasm happened to coincide with the moment at which the needle, after deflection by the nerve current, had returned to rest, it swung back several degrees at the commencement of the spasm. The experiment is, however, most uncertain, and depends upon various irregular conditions. On the other hand, there is regularly, on exciting the motor zone of the cerebral cortex, a negative variation of the longitudinal-transverse current in the spinal medulla, expressed on the capillary electrometer as a succession of rhythmical oscillations, occurring simultaneously with epileptic spasms in the muscles.

In opposition to the marked effects on leading off from longitudinal and transverse sections of the spinal cord, there is, as was shown by Gotch and Horsley (5), very little result from leading off at the cut end of the sciatic nerve, during excitation of the motor zone. According to Horsley's observations the excitation diminishes on its way from the cord to the mixed nerve, by more than 80 per cent. The same difference appears when the fibres of the corona radiata, instead of the cortex, are directly excited.

If it is thus established that efferent impulses from the centres, however excited, produce a negative variation of the nerve current, more recent observations seem to establish the same for sensory impulses also. Du Bois-Reymond made experiments to see whether excitation of the natural ending of a sensory nerve by an adequate stimulus might not result in movement of the multiplier-needle, instead of in sensation (just as the motor nerve in the above experiment with strychnine had displaced the magnet, and not the muscle). He obtained a negative variation on the frog's sciatic when the leg, with the skin *in situ*, was progressively scalded with boiling salt solution from tendon to knee, or corroded and burned with concentrated sulphuric acid (23). Yet, as du Bois-Reymond himself pointed out, this was rather "tetanising of the sciatic through its cutaneous branches," than excitation of the sensory end-organs of the skin. Kühne (9) in fact found that the negative variation

persisted when the skin was stripped off before scalding to a ligature at the foot, and then lifted back as far as the knee, after dividing the cutaneous nerves, or removing them completely. On the other hand, he succeeded (9) in demonstrating *the negative variation of the optic nerve* on stimulating the retina with light, in the eye of the pike, as, later on, in that of the perch, and still more perfectly in the frog's eye. It is therefore certain that the current of the sensory nerves reacts in this case to the highly-specialised excitation of the epithelial end-apparatus by light, exactly as that of the mixed or motor nerve reacts to excitations of all kinds, it being immaterial whether the stimulation proceeds from the central ganglion-cells, or whether it impinges upon the continuity of the nerve itself, as a mechanical, chemical, thermal, or electrical stimulus. In every case it is the same negative variation of current in the nerve that appears as the concomitant of excitation, and this is one of the main supports of the prevailing theory of the physiological homogeneity of all nerve-fibres, and of the identity of the excitatory process within them. It is a striking fact "that the optic nerve, during the continuous stimulation of its terminal organ by light, gives no different reaction from that of a tetanised nerve, under discontinuous electrical stimulation. If in the last case we have reason to believe the galvanometer inadequate to show the presumptive discontinuity of the variation, we must in the former instance accept its evidence, since there is no reason to suppose that the immediate effects of sustained illumination are, like most other tetani, discontinuous" (Kühne).

This persistent diminution of current in the optic nerve may be termed *phototonus* (Kühne). It is a striking fact that the close of the illumination, *i.e.* cessation of excitation by light—"or, more properly, the resumption of certain retinal processes interrupted by light—is also marked by a final negative variation of the optic nerve, which cannot be interpreted otherwise than as a repeated excitation traversing the nerve." If "phototonus" is thus a sign of activity in the optic fibres, we may justly conclude with Kühne (*l.c.*) "that the cutting-off of light is able to produce a greater effect upon the central organ, and to discharge a more intense sensation (excitation), than the prolonged action of the same light upon the eye."

At the same time we cannot overlook the fact that the

similarity of electromotive reaction in the two cases proves nothing as to qualitative equality of chemical process. Hering points out that "we must hesitate, in view of the endless variety of the different chemical processes by which electrical currents are engendered, to affirm an equality of internal process in the nerve from the similarity of electromotive reaction in two nerve-fibres (more especially in those of which the excitation produces very dissimilar central and peripheral reactions), or in one and the same fibre under different conditions: or to exclude the possibility that different kinds of internal alteration may be transmitted within certain nerves, or even to assume the same process for all nerves (with the single possible exception of certain sensory nerves)." "Muscle, gland-cells, plant cells, perhaps indeed all living substances, exhibit under certain conditions an electrical reaction, which from its very commencement presents a striking analogy with the electrical reaction of nerve. Should we therefore" (continues Hering) "conclude that the internal chemical processes which are the cause of these manifestations are alike in all parts of the living substance, or that when the same electrical effects occur in two cases within the same substance the underlying chemical alterations must necessarily be the same?" (Hering, 24, p. 19 ff.) From this point of view it is, if surprising, at least intelligible that the presumably assimilatory, cardiac inhibitory, vagus fibres, the excitation of which produces a positive variation of the muscle current, should, even as regards their galvanic reaction to excitation, differ in no respect from other nerve-fibres.

S. Fuchs (25) has recently communicated some interesting observations upon the negative variation of centripetal nerves during adequate excitation of their peripheral end-organs. The Selachians, and notably the *Torpedinidæ,* possess a special system of canals beneath the skin, which partly open under the skin (Lorenzinian ampullæ and pectic tubes), and partly form blind sacculæ (Savian bladders), but are always intimately connected with the nervous system, and are undoubtedly sense-organs. In *Torpedo,* the Lorenzinian ampullæ are globular sacs divided into four compartments by partition walls. These sacs are enclosed in a special capsule, of which there are two pairs in *Torpedo;* one pair lies in the nose exactly in front of the eyes, and contains, according to Leydig, about 100 ampullæ in the two capsules, the

canals for the most part opening against the wall of the body. The second pair of capsules lies farther back, at the external wall of the electrical organ. The system of Savian bladders consists of saccules 2–3 mm. in diameter, which in life are perfectly transparent. These occupy the four-sided space between the anterior ends of the electrical organ as far as the upper lip, and extend still farther backward. "Each sac consists of a homogeneous membrane of connective tissue, and is filled with a clear gelatinous mass. The ingoing nerve forces its way through a peculiar felted tissue, which lies like a cushion at the lower part of the bladder; it then divides into three branches, of which the central is the strongest. Each of these forms a kind of expansion, which supports the true sensory epithelium (hair-cells resembling the auditory cells of the organ of Corti). In the cervical region this structure is supplied by the trigeminal nerve, in the region of the trunk by the vagus.

After extirpation of brain and cord, the trigeminus (which supplies the lateral ampullæ and Savian vesicles) was dissected out, the central end of the nerve, which is 2–3 cm. long, being laid by its long and transverse sections across unpolarisable electrodes; there was then a distinct, if small, deflection on the galvanometer, in the direction of a negative variation, each time the skin was lightly compressed above the lateral packet of Lorenzinian ampullæ and Savian vesicles. It was subsequently found that the last alone are responsible for the effect.

This is, therefore, the second authenticated case in which *excitation of the peripheral end of a sensory nerve by adequate stimuli produces negative variation of the demarcation current in the divided trunk of the nerve.* Obviously there is here a wide and still unexplored field.

The electromotive changes in the central endings of the superior sensory nerves—*i.e.* the sensory cortical regions—in consequence of adequate excitation of the peripheral sense-organ (eye, ear), are of the greatest interest, although theoretically still obscure: this is not, however, the place to discuss them. We must now return to the negative variation of peripheral nerves under artificial excitation.

IV. Time-Relations of Action Current as determined by Rheotome

If a single brief stimulus, *e.g.* an induction shock, is sent into the nerve, the existence, much less the time-relations of the negative variation, will hardly be recorded by the galvanometer, owing to the sluggishness of its magnet. We are therefore driven back upon the repeating method, with the rheotome, for the solution of the questions already familiar to us in muscle. The method and instrument have already been described (vol. i. p. 367).

Bernstein (26) found, in investigating the course of the negative variation of the nerve current with tetanising, electrical stimulation, that there was a measurable period between the excitation of any point of the nerve and the commencement of a negative variation (i.e. *negativity*) at a more distant lead-off, corresponding with the rapidity of transmission of the negative variation in the nerve, and the distance between the point of excitation and the first longitudinal contact. The distance between excited point and transverse section, on the other hand, is immaterial. From this we may conclude, as in muscle, that the process of negative variation in the part led off begins at the precise moment in which the excitatory process transmitted in the nerve arrives at the longitudinal electrode. It is further evident that there is no perceptible interval between the moment of stimulation by induction currents and the commencment of negativity at the excited point. *The negative variation has no latent period.* Both in medullated and non-medullated nerve the negative variation is transmitted at a rate corresponding with that of excitation, so that the negativity of any point of the nerve may, as in muscle, be accepted as the galvanic expression of excitation. Fuchs (4) determined the transmission rate of the negative variation in cephalopod nerves as something between less than 1 m. and 3·5 m., according to temperature. *Within a given range it increases with strength of stimulus.*

The process of negative variation within a tract of nerve is further found, on leading off from longitudinal and transverse sections, not to be instantaneous, but to last for a measurable period. It does not at once attain its full strength, nor does it disappear immediately. Experiment rather shows that negativity rises (at

the longitudinal lead-off) after a single stimulus, within a certain limited period, to its maximum, and slowly disappears again.

According to Bernstein's method (in which that arrangement of the slider is determined on the rheotome, which gives the beginning and ending of the variation, the time occupied by the galvanometer closure being then subtracted from the total period of difference between these two positions) the duration of the negative variation does not exceed 0·0007 ($\frac{1}{1430}$) sec. in medullated frog nerve. This very low, and theoretically improbable, figure is as a matter of fact incorrect. Hermann (27) claimed a much longer period for the negative variation (= 0·0056 sec.), while Head (10), by means of Hering's specially-constructed rheotome, estimated it at 0·024 sec.—*i.e.* a value more than thirty times as great as that of Bernstein.

The duration of the negative phase varies with the state of the frog from 0·0079 to 0·0239 sec. Hermann at first referred this extension to his system of cooling the nerve, as retarding the transmitted excitation, and corresponding negativity, of each element of the nerve. Further experiments, however, showed that even at normal temperature the variation takes longer than was stated by Bernstein. Hermann then concluded that his use of a highly-sensitive galvanometer, and packet of six nerves, were responsible for the more complete expression of the last part of the declining variation. The far larger figure given by Head implies that his rheotome followed the descending portion of the curve in each single negative phase, beyond that employed by Bernstein: the longer closure of the galvanometer circuit magnifies the effect of the variational, or action, current upon the magnets, and multiplies it much more with increased stimulation-frequencies than was possible to Bernstein and Hermann (Fuchs, 4).

Head's experiments show that the magnitude of the negative variation is chiefly conditioned by the magnitude of the nerve current. On the other hand, it is to a remarkable degree independent of fatigue in the nerve (according to Fuchs, there is some relation between the two in non-medullated nerve), in which respect it behaves quite differently from the positive after-variation. Lastly, the duration of the single negative phase is shown to be affected in a marked degree by the condition of the frog. In winter frogs there is a comparatively prolonged single negative phase, although the total negative variation is, relatively

speaking, small; in spring frogs the single variations are short, with comparatively large total effects.

In the non-medullated nerves of Cephalopoda, Fuchs (*l.c.*) estimates the average duration of the negative variation with stronger stimuli at 0·0113 sec., with weaker excitations at 0·0082 sec., *i.e.* a value intermediate to those given by Bernstein and Head. With a method corresponding to that of Hering and Head, the duration of the negative variation would no doubt be found even greater than Head's estimate of it in frog nerves.

Fuchs further investigated the significance of the retarded variation of non-medullated nerve, and indicated a possible relation with the slow rate at which the excitatory process is transmitted. If (as cannot be doubted) the transmission of excitation does really depend upon some sort of propagation from section to section, the prolonged duration of the process must be advantageous, and we know experimentally that non-medullated is far less sensitive to very brief stimuli than medullated nerve.

These facts show that the tetanic negative variation is rhythmically discontinuous, and (notwithstanding its apparent steadiness) of an oscillatory character in nerve as in muscle. We have next to ask what magnitude can be reached by the single negative swing on strengthening the stimulus? Will the demarcation current corresponding with the maximum of the variation fall each time to zero, or even reverse itself (as Bernstein found in medullated frog's nerve); or will there merely be (as in muscle) greater or less diminution of the existing P.D., in the rhythm of the stimulation? The question in both cases can be decided by the rheotome method, on making the galvanometer closure as short as possible, and then finding that position of the slider which corresponds with the maximum of the variation. If compensation is then cut out, and that fraction of current measured which is sent by the rotating rheotome into the galvanometer circuit, and the tetanising key opened, it can be seen at once whether the variation is less than, equal to, or greater than the current of rest. By such experiments Bernstein determined the negative variation with an augmented stimulus to be much in excess of the current of rest, in frog's nerve. On repeating the experiment Hermann (27, p. 385) at first found the variation to be much less than the current of rest, and

Bernstein (28) himself doubted the accuracy of his observations. In the end, however, Hermann confirmed Bernstein's original statement, on leading off from a *mechanical* cross-section (made by crushing), and not from a *thermal* section, in which the fine nerves may be injured by the steam from the hot water. He then repeatedly observed cases in which the negative variation was nearly double the current of rest. But, as Head (*l.c.* p. 241 f.) showed in theory, if we start from the low value quoted by Bernstein for the duration of the single negative phase (0·0007 sec.), the variational current (*i.e.* current through the galvanometer in consequence of negative variation) must at the moment of maximal intensity be $4\frac{1}{2}-9$ times as strong as the nerve current: which is highly improbable, "so long as the intensity of the exciting induction currents is kept within the (narrow) range in which direct excitation of the nerve by unipolar action in the part led off (galvanometer tract) is absolutely excluded." His own experiments (which, owing to the method employed, failed to determine the intensity of the variational current directly, and only gave the *minimal* indispensable height of the negative variation, not—as in Bernstein's experiment—its actual height) afforded no indication of variational currents of such magnitude as was assumed by Bernstein and Hermann.

In the non-medullated nerves of Cephalopoda, Fuchs invariably found that, "at that position of the rheotome slider which corresponds with the maximum of the negative variation, the latter only induced a more or less considerable diminution of the current of rest—never its abolition, or even reversal."

It is far harder to demonstrate a phasic action current between two longitudinal points of the uninjured nerve, than on leading off from long and (artificial) transverse sections. As we have stated, Bernstein was the first to show on striated muscle that during the passage of a directly-stimulated wave of excitation the points over which the wave was passing were invariably negative to all other (unexcited) points. Hermann extended this law to the natural ends of the uninjured muscle, as well as to the case of indirect excitation, and proved the *universal* presence of a diphasic action current in all uninjured muscles, those of man included. It is plain that a similar reaction might be anticipated for nerve: the difficulties of experiment are equally apparent. Owing to the extreme rapidity

of conduction in nerve, the interval at which the wave passes the two leading-off contacts is too small to be analysed by the rheotome, even when the electrodes are far apart; while on extending the tract led off, the resistance, which is already considerable, increases so much that the effect becomes imperceptible.

Hermann, however, overcame these obstacles; he depressed the rate of conductivity by cold, and employed bundles of 4–6 sciatics. He was then able to obtain a distinct separation of the two opposite currents with the rheotome, and thus established the undulatory character of that alteration in the nervous substance, which in the galvanic expression of excitation is characterised by negativity.

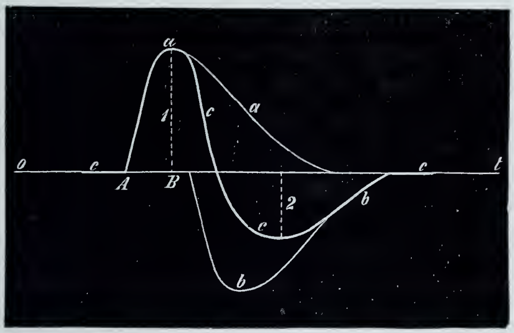


Fig. 202.

If one lead-off is at the artificial transverse section, the corresponding phase fails, as in muscle, or is at any rate "rendered uncertain." Hermann found, without exception, that the second phase was less conspicuous and more prolonged than the first; this is not, however, due, as in muscle, to decrement of excitation, but refers strictly to the fact that the first phase has not nearly expired when the second is at its maximum. This is clear from the accompanying diagram (Fig. 202, from Hermann). "The abscissa *ot* represents the times, positive ordinates the homodromous, negative ordinates the heterodromous direction of current. The curve *Aaa* gives the temporal relations of the action current from the first lead-off, *Bbb* that of the action current from the second. *AB* is the time required for transmitting the excitation between the two leading-off contacts. *Accc* is therefore the curve of the resulting diphasic current of action, the second phase (2) of

which is lower and more extended than the first phase (1), and, moreover, reaches its maximum at a different point from the maximum of excitation at the second lead-off. The superficies of the parts of the curve corresponding with the two phases must be equal; hence their action upon the galvanometer ceases simultaneously in tetanus."

In muscle, we have in the physiological rheoscope and its secondary excitation an exceedingly convenient indicator of the discontinuous nature of the negative variation of the demarcation current, as well as of the action current in the uninjured and intrinsically isoelectric muscle. Du Bois-Reymond tried in vain to obtain secondary excitation from one nerve to another, and later experimenters were no more fortunate, so that it seemed impossible to decide from one excitable nerve whether another was or was not excited. This is contrary to what we should have expected *a priori;* for the electrical variation in nerve is, absolutely and relatively, a more vigorous process than that in the muscle, and there is no sufficient reason why (to all appearance) no nerve has an excitatory action upon another superposed upon it. Hering (11) has now, indeed, established the possibility of true secondary excitation from nerve to nerve, by availing himself of every advantage, the increased excitability in the vicinity of an artificial transverse section included. If the peripheral end of an excitable sciatic (exposed from vertebral column to knee, and cut at both ends) of a cooled frog is applied to the central end of a second nerve still connected with the leg, so that the two nerves lie together for 5–6 mm., and their cross-sections are in the same place, then the demarcation current of the one nerve will, as it were, compensate that of the second. "Supposing the longitudinal-transverse current suddenly to disappear from the peripheral end of the primary nerve (through negative variation to zero) in consequence of an instantaneous excitation, the compensation of current in the second nerve will be abruptly abolished. The end of the primary nerve that in consequence becomes isoelectric, now functions solely as a shunt to the current of the secondary nerve, and the latter will be weakly excited by the sudden short-circuiting of its own current. But if the direction of current in the exciting nerve is reversed, it will after reversal act upon the second nerve like a weak descending current, and summates with

the intrinsic and suddenly short-circuited current of this nerve" (Hering).

If under these conditions excitability is heightened as much as possible by making a new transverse section simultaneously at the peripheral end of the primary and central end of the juxtaposed secondary nerve with a scissors-cut, and then weakly tetanising the central end of the primary nerve, Hering invariably noted a weak tetanic disturbance of the secondary preparation. Current escape and unipolar stimulation were excluded, since the weak exciting currents only took effect when the electrodes were placed near the transverse section, all secondary action failing when they were applied to other points of the primary nerve nearer the second preparation. Electrotonic action is excluded by the great distance between the point of stimulation and the position of the secondary nerve, so that the possibility of true secondary excitation from nerve to nerve was no longer doubtful. Obviously, the result would be even less ambiguous if the tedious process of applying the two nerves together could be replaced by a preparation in which the bundles of nerve-fibres serving as primary and secondary nerves should lie naturally in a common sheath. Hering accordingly, in a cooled frog, exposed the sciatic nerve above the knee, ligatured its two branches together, divided them below the ligature, dissected out the nerve to the place where the branch is given off to the thigh, and then divided the sciatic plexus, and (when the muscles were quiet again) stimulated the knee-end of the nerve with weak currents. The muscles—of which the nerves were still in connection with the plexus—fell at once into strong secondary tetanus. The experiment never fails, provided the preparation be so excitable that the division of the sciatic plexus produces a slight muscular disturbance in the leg, in addition to the twitch, and that there is a fresh transverse section. The proof that this is not due to current-escape, electrotonus, or unipolar excitation, again lies in the fact that there is regularly no effect so soon as the electrodes are moved slightly away from the cross-section, and approximated to the muscle. In three preparations, moreover (and in two cases, twice or three times consecutively), a weak partial twitch of one of the muscles of the thigh was observed by Hering on crushing the primary nerve. This, together with the inevitable failure of other kinds of stimuli, is hardly surprising, in view of the difficulties (*supra*)

of eliciting any considerable negative variation of the nerve current by other than electrical stimulation. V. Uexküll (29) has recently obtained positive results from his mechanical tetanomotor, and has, moreover, proved the justice of Hering's presumption, that the whole effect will fail, or die out, even under electrical stimulation, if the long and transverse sections of the plexus are brought into circuit by dipping them into physiological saline before, or during, the appearance of the current of action.

V. Electromotive Changes (Electrotonus)

1. *In Medullated Nerve*

It has already been stated that polar alterations of excitability appear under the action of a battery current, flowing

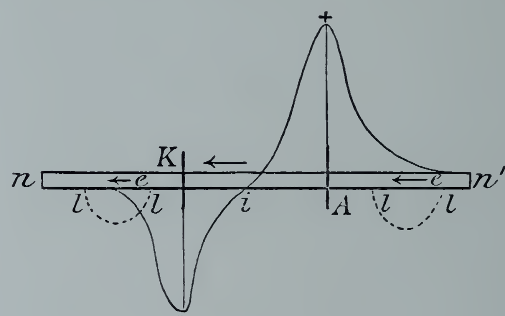


Fig. 203.

steadily at uniform density through any portion of a medullated nerve. These changes are not (as in muscle) confined to the points of contact with the electrodes, *i.e.* the visible entrance and exit of the current, but extend beyond them, not merely into the intrapolar tract, but to a greater or less extent over the extrapolar region also. As early as 1843 du Bois-Reymond showed that there were corresponding changes of galvanic reaction which, like those of excitability, must be diagnosed as one of the manifestations of electrotonus, representing in some degree two different sides of one process. Let nn' (Fig. 203) be a nerve, A and K the two electrodes through which a battery current is led in the direction A–K; A is therefore the anode, K the kathode, of the current that produces electrotonus. On making this current, all

points of the nerve lying on the kathodic side (k–e) become more negative, all points on the anodic side (A–e) more positive than before. These alterations are, however, unequal in degree at different points, being greater in the vicinity of the electrodes, and less at a distance from them. If the positive increment from A–e is represented by lines, the height of which expresses the increase, and if the heads of these lines are joined together, the resulting curve represents the alterations of potential occurring at the respective points. The alterations on the kathodic side may be similarly expressed, only here the ordinates must be drawn downwards from the nerve as abscissa, to show that the potential on this side is negative. The two parts of the curve represent the state of the extrapolar regions. As a matter of fact we do not

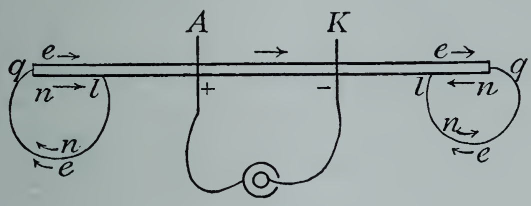


Fig. 204.

know the reaction of the intrapolar tract, because it is impossible (on technical grounds) to investigate this area. We can only presume that the alterations of potential there are such as are expressed by the connecting line i. These curves do not of course represent actual magnitudes of potential at given extrapolar points, they merely express the general fact that there is a diminution from the poles outwards.

Since the nerve to be examined is usually bounded by two cross-sections, and is thus *ab initio* electromotive, there must, with a suitable lead-off, be interference between the demarcation current and the electrotonic increment, which is of course always in the same direction as the polarising current. This produces at one end of the nerve a negative, at the other a positive variation of the longitudinal-transverse current, lasting as long as the closure of the polarising battery current (Fig. 204). If the electrodes are shifted from the cut end towards the centre, there will obviously be deflections in the galvanometer, on either side of the tract traversed by the current, in the direction of the polarising current. And this will equally be the case when the

nerve, with both ends cut, is isoelectrically disposed, *i.e.* is in contact with the galvanometer electrodes at points symmetrical with the equator, laterally to which it is traversed by the polarising current. The situation may then be expressed as follows:—*If a constant electrical current is led through a portion of a medullated nerve, the entire nerve (while preserving its original electromotive activity) becomes electrically active in the direction of the polarising current at all points, each point of the nerve being negative to every other that is anterior to it in the direction of the current.*

The magnitude of the electrotonic deflections diminishes (as is *prima facie* obvious from the distribution of potential) with the distance of the leading-off tract from the poles, as appears plainly in the vicinity of the latter; it is further in ratio with the strength of the polarising current. Moreover, the electrotonic effect increases constantly with increased intensity of current, and never seems to find a limit. Certain experiments of du Bois-Reymond (23), which were intended to determine the eventual maximal value of electrotonus, were unsuccessful, although they showed that the E.M.F. of the incremental current on the side of the anode and kathode (Grünhagen's anodic and kathodic current) may exceed that of the normal longitudinal-transverse current by more than twenty-two times, without finding a limit. As expressed in units of a Daniell, the E.M.F. of the anodic current = 0·5 Dan., that of the kathodic current 0·05 Dan. This difference of E.M.F. in the an- and katelectrotonic incremental currents, which finds similar expression in regard to intensity, is distinct in every case, and is the reason that in a graphic representation the curves of potential are shorter upon the side of the kathode, and the corresponding ordinates lower, than on the anodic side (Fig. 203). *Under all conditions the maximum of anelectrotonus exceeds that of katelectrotonus.*

A further factor in the magnitude of electrotonus is *the length of tract traversed by the polarising current.* If the electrodes are gradually shifted so as to lengthen the tract of nerve excited, the incremental currents diminish *pari passu* with the extension of the tract through which current is passing; this diminution is, however, obviously due to the weakening of the polarising current, from the increased resistance of the conductor. If (as was first effected by du Bois-Reymond) the intensity of the polarising current is kept constant by introducing

a high resistance (tube of alcohol) into the polarising circuit, or ligaturing the intrapolar tract with a moist thread, the magnitude of electrotonic increment increases with the extension of the electromotive tract traversed by the current, or *vice versa* diminishes with its restriction. *The direction of the polarising current in relation to the long axis of the nerve* has, moreover, a great effect upon the intensity of electrotonic action, and the increment, like the excitation, is found to be greatest when the polarising current flows longitudinally through the nerve—*nil* with transverse passage of current.

As regards the theory of electrotonic action, its dependence upon the constitution and state of the nerve is of the first importance. The conjecture that it is due to ordinary current-escape in the galvanometer circuit is at first sight plausible, in view of the entire reaction, but is at once refuted by the fact that dividing, or crushing of the nerve, between the polarised and leading-off tracts, abolishes all sign of excitation. This proves that the diffusion of electrotonus, as of excitation, is correlated with uninterrupted continuity in medullated nerve. And it is not merely the complete interruption of conductivity, but every modification of it, or of excitability (*Leistungsfähigkeit*) in the nerve, that affects the magnitude of electrotonus in a greater or less degree. No electrotonic action, or at most only a trace of the ordinary effects, can be detected on dead nerve, or nerve that is fundamentally altered in its physical and chemical properties. *The entire manifestation is indisputably bound up with certain structural peculiarities that are present only in living, uninjured medullated nerve.* The utmost importance attaches to the fact (to be discussed below) that—under uniform conditions—the electrotonic incremental current, in the above sense, does not appear either in non-medullated nerve, or in muscle, or other moist conductors (wet threads), so that *the presence of a medullated sheath seems to rank first among the necessary structural requirements.*

The fact that division of the nerve between polarised and led-off tracts prevents the development of electrotonus, even when the cut surfaces are replaced as carefully as possible, leads on to the question whether the underlying alterations are, like excitation, *transmitted* at measurable velocity in the nerve. After du Bois-Reymond had shown that the development of

electrotonus takes no appreciable time, since it appears at full strength immediately after closing the polarising current, and can be demonstrated with even the most fugitive induction currents, Helmholtz was the first to prove the same fact by means of the physiological rheoscope (31).

In view of the known sensibility of the latter to much weaker currents than are here under consideration, it is quite intelligible that the electrotonic incremental current should be adequate to excite the nerves of a rheoscopic frog's leg, if properly led through it. It is even possible (as du Bois-Reymond showed) to throw a superposed nerve into secondary electrotonus, by the electrotonic incremental current of the first nerve. If one end B (Fig. 205) of a medullated nerve polarised at A is applied to a second nerve CD by part of its length, the second nerve at once falls into a state of electrotonus; the end D is, however, at the opposite phase to B, since the incremental current at B flows through the end C of the applied nerve, which forms a shunt circuit in the opposite direction. If this nerve is still connected with its muscles, then both at make and, under favourable circumstances, at break of the polarising current there will be a secondary contraction, which is not to be confused with the true secondary twitch from nerve to nerve caused by the current of action, as first demonstrated by Hering. Du Bois-Reymond's "paradoxical twitch" is a very interesting form of this secondary contraction depending on electrotonus. The conditions for the discharge of this secondary twitch by the electrotonic incremental current are especially favourable when the fibres of the two nerves, in so far as they are in juxtaposition, are as it were coherent, *i.e.* fused into a single stem. This is the case in the frog's sciatic with the two branches into which it divides at the knee (*peronæus* and *tibialis*, Fig. 206). If one or the other is non-electrically excited, the muscles innervated from that branch alone become active, never those from the other. If, however, an electrical current is passed through the tibial branch at a point not too remote from the bifurcation, contraction occurs at make and break not merely in the muscle A but also in B, which is supplied by the peronæal branch, because the primary

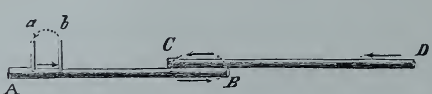


Fig. 205.

electrotonic nerve throws the other nerve forming with it a common trunk into secondary electrotonus. Since even brief impacts of current, or induction shocks, have an electrotonic effect, it is clear that secondary tetanus may readily be induced by tetanising the primary nerve. The excitatory action of both primary and secondary electrotonus increases rapidly with approximation of polarised to led-off tract (as might be anticipated from the marked rise in potential near the polarised tract). In this we have apparently (*supra*) a means of distinguishing between the *true* secondary excitation from nerve to nerve, and the paradoxical contraction (Hering, 11).

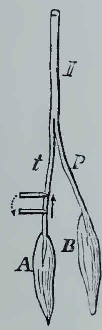


FIG. 206.

Helmholtz made use of the latter as follows, in order to determine the time occupied in establishing the galvanic changes in electrotonus. A second, isolated nerve was applied to a sciatic still in connection with the gastrocnemius, in such a way that the half of the nerve proximal to the recording muscle was brought into contact with the corresponding half of the other nerve (Fig. 207). Electrotonic stimulation of corresponding points at the central end of the two nerves yielded two twitches in succession, one produced by direct excitation of the nerve to the muscle, the other by secondary electrotonus. The secondary contraction from the nerve was not found to enter perceptibly later than the primary twitch, whence Helmholtz concludes that "the electrotonic state does not make its appearance demonstrably later than the electrotonic current which excites it," and does not therefore, like excitation, require a measurable period in which to diffuse over the extrapolar region. Du Bois-Reymond (6, p. 258) had already pointed out that Helmholtz's experiment, strictly speaking, can only mean that the changes fundamental to electrotonus, and the process of excitation, are transmitted at *equal* rapidity in the nerve. This follows directly from Hermann's words (19, p. 162). "If the interval between excitation and contraction of the muscle [*M*, Fig. 207] is the same, whether *a* or *b* be excited, this proves that the electrotonus, in order to spread in the first nerve from *a* to *c*, requires as much time as is taken by the excitation to spread in the second nerve from *b* to *c'*. But if the electrotonus at *c* is strong enough to excite the second nerve, it will certainly produce direct excitation at *c'*, at least as strongly, when it is directly produced by excitation of *b*

in the second nerve; in other words, at the strength of current employed, the second nerve is directly excited as far as c', as soon as the current is applied at b: thus the experiment only shows that the electrotonus spreads in both nerves with equal rapidity, and gives no conclusions as to the rate of this transmission.

Another series of experiments refers to the time-development of the electrotonic changes of excitability, which—as was pointed out by Pflüger—are in close relation with the galvanic effects, and, as it were, merely represent another symptom, or another side of the same underlying process in the nerve. It is therefore legitimate to draw conclusions from the temporal distributions of the one alteration to that of the other. Pflüger (32) has, moreover, demonstrated by direct experiment, at least for anelectrotonus,

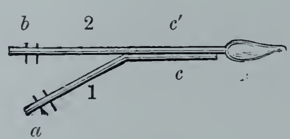


FIG. 207.

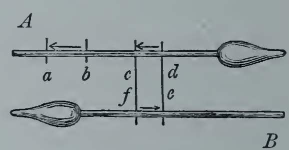


FIG. 208.

that the alterations of excitability appear simultaneously with the galvanic alterations.

If (Fig. 208) a strong ascending current (*ab*) is passed steadily through the central end of the nerve of an ordinary nerve-muscle preparation, the myopolar portion of the nerve falls into anelectrotonus; the corresponding incremental current can be led off by a second pair of electrodes (*cd*) situated within the same region, to the nerve B of a second preparation, so that this is traversed at the same distance from the muscle, but in the opposite, *i.e.* (in the respective position of both preparations) ascending direction. As soon as the primary nerve (*cd*) becomes electromotive, under the presumption of a transmission of electrotonic alteration at given rapidity from the polarised region *ab*, a branch current passes at the same moment through *ef*, and produces secondary excitation in this nerve. From the fact that it is invariably the muscle (B), and never that of the primary preparation (A), that twitches, Pflüger concludes that at the time when the electrotonic incremental current traverses the tract (*cd*) of the first nerve - muscle preparation, and excites the second muscle to secondary (paradoxical) contraction, the same incremental current which excites the second muscle leaves the first at rest; *i.e.* in

other words, the alteration of excitability is present simultaneously with the corresponding galvanic alteration.

Subsequent experiments undertaken by different workers in the hope of deciding this question (*i.e.* the absolute time occupied by development of the electrotonic alterations in the nerve after closure of the polarising current) have not so far produced any congruous results. According to Wundt (33), who undertook a comprehensive inquiry into the time-distribution of the electrotonic alterations of excitability in the frog's nerve-muscle preparation, these changes are not developed simultaneously with the closure of the polarising current at all points of the nerve, but spread from the poles with comparatively low and easily measurable rapidity from section to section by an undulatory process analogous with that of excitation. In this sense Wundt speaks of an "*anodic wave of inhibition*" (*i.e.* an altered state of the nerve-substance, characterised by diminished capacity for response), transmitted from the anode at a rate that varies with the strength of the polarising current from 80 to 1700 mm. per sec.; and a *kathodic wave of excitation* (*i.e.* katelectrotonic rise of excitability), of which the rate of transmission appears to correspond with that of active excitation. In regard to method, it is sufficient to state that it consisted essentially in exciting different points of the myopolar part of the nerve, at different periods after the closure of an ascending, or descending, polarising constant current, with single induction shocks, and then recording the discharged contraction graphically. The differences which then appear in regard to time-distribution, the magnitude (height), and duration of twitches, before and after closure of the polarising current, form the basis of conclusions as to the state of excitability at any point of the nerve at a given moment. Wundt's observations, into which we cannot here enter in detail, seem to have been little regarded; they are in direct contradiction with Pflüger's experiment, as described above, and also with certain experimental results of Grünhagen (34), in which the commencement of the electrotonic alteration of excitability coincides, at all points of the nerve, with the moment of closing the polarising current. If (Fig. 209) a rheochord (rr^1) and the primary coil of an induction apparatus are included in the polarising circuit (K), a branch of the primary current may be led into the nerve of a nerve-muscle preparation (cd) in an ascending direction. Although in itself inadequate to excite

the muscle, it is sufficient to cause a demonstrable anelectrotonic depression of excitability within the myopolar part of the nerve. With sensitive preparations, the height of the twitch discharged at

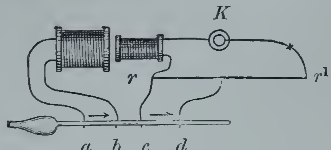


Fig. 209.

ab by the ascending make induction shock was then regularly less when the region *cd* was simultaneously polarised by a branch of the primary current. To Grünhagen's conclusion that the anelectrotonic depression of excitability at *ab* existed previous to the induction closure, *i.e.* coincided with the entry of the polarising current, Tschirjew (35) objected that with the combined action of the two currents, the induced exciting current must necessarily be weaker than in the other case, because a part of the inducing current would now be led into the nerve by the rheochord. But this objection is, as Hermann (35) subsequently pointed out, of no weight in view of the relations of resistance; since it can hardly be of consequence to the current in the primary coil of low resistance (1–2 Siemens' units), whether a branch current, sent into the nerve with its 40,000 to 70,000 units, is made or broken, as was also demonstrated experimentally by Baranowsky and Garré (35, p. 449).

Tschirjew's experiments on the rate of transmission of galvanic as well as excitatory charges in medullated nerve during electrotonus led him to conclusions fundamentally different from those of his predecessors, and his views were subsequently confirmed by Bernstein in an investigation which we have not yet referred to. He stated that the electrotonic alterations in nerve are transmitted *at a rate approximating to that of excitation, but, generally speaking, somewhat lower.*

In order to determine the rate at which the anelectrotonic decrease of excitability in the nerve is transmitted, Tschirjew employed a method analogous to that of Wundt.

"The minimal stimulus which will discharge a twitch is determined at any point of the nerve in a frog's gastrocnemius preparation. A strong ascending current is then made in the part of the nerve proximal to the central end, at a certain distance from the point of excitation. Closure of this current of course evokes no twitch under these conditions. After a certain brief period the excitability of the nerve is tested again at the former point. If the

earlier minimal strength of excitation still produces a perceptible twitch, the interval between this excitation and the closure of the polarising current is lengthened, and the experiment repeated. This is continued until the minimal excitation remains without effect." "The interval between the two closures gives the time occupied by transmission of the decreased excitability from the intrapolar tract to the excited point. If this distance were taken, the required rate of transmission could be deduced from it."

In order to determine the appearance of the galvanic alterations of electrotonus at a point of the nerve beyond the polarised part, two points symmetrical to the electromotive equator are in the first place uninterruptedly led off, and existing differences of potential compensated. This circuit, which included a sensitive galvanometer, could be opened by means of a spring myograph, at different times after brief closures of a battery current, that traversed the nerve in an ascending or descending direction at a given distance from the leading-off tract. The interval between closure of the polarising current in the nerve, and the opening of the galvanometer circuit, could thus be varied at pleasure. It is clear that the determination of the time required between this last and the closure of the polarising current, in order to detect the first trace of electrotonic variation of current on the galvanometer, must also determine the time required by the latter in every case, for its transmission from the polarised to the led-off tract. Both series of Tschirjew's experiments were severely criticised by Hermann (36), who emphasised the fact (as regards Tschirjew's galvanic measurements) that, as will presently be shown, the *electrotonus at any given point of nerve does not reach its full intensity at the first minute, but increases gradually.* "And if the electrotonus immediately after its origin is weaker by only a quarter of its total amount, the results of Tschirjew are quite compatible (as Hermann points out) with an instantaneous appearance." The same of course holds good of the experiments in which the time to be determined is that which must elapse after closure of the polarising current, in order to produce anelectrotonus at a distant point of the nerve sufficient to suppress the twitch called out here by a test stimulus. "This interval is not, however, identical with that which must elapse before the commencement of anelectrotonus at that point of the nerve," but probably shorter. Consequently, as Hermann

pointed out, the electrotonic alterations (unlike excitation) diminish rapidly in intensity with increasing distance from the polarised tract, and finally become imperceptible. So that, when immediately after closure of the polarising current the electrotonus is still undeveloped, the region in which it can be demonstrated is necessarily even smaller than that in which it appears definitely.

Tschirjew subsequently repeated his experiments with the same results, using the capillary electrometer (which is peculiarly sensitive to rapid oscillations of current), and Bernstein's rheotome,

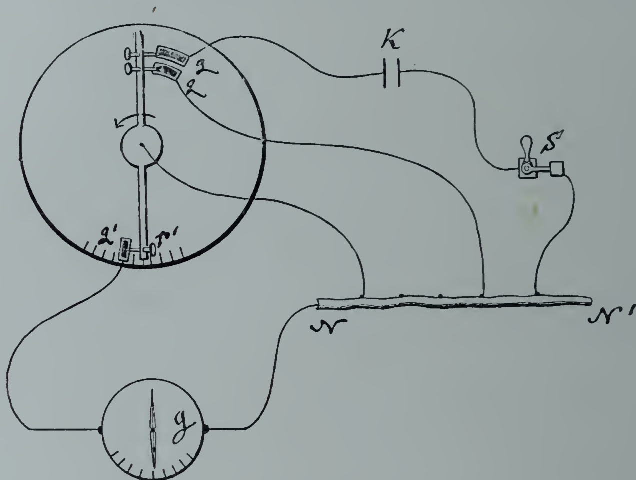


FIG. 210.

which of course are open to the same objections. Bearing in mind the theory of this last ingenious instrument, it is evident that it affords an easy means of leading a polarising current at any given moment into the nerve, and interrupting it again directly, at the same time leading off the electrotonic currents from a distant tract of the nerve at different intervals after closure. Bernstein's own method of experiment (as referred to above) is explained by the following schema (Fig. 210). During the rotation of the rheotome the polarising current is periodically closed whenever the contacts dip into the mercury pools (qq), the galvanometer circuit as often as the contact (p^1) dips into (q^1). The period of closure of the polarising current varies between $\frac{1}{80}$ and $\frac{1}{200}$ sec.; the direction of the led-off current

(which is closed by altering the position of the slider on the rheotome at any given moment between the closure and opening, or after the opening of the polarising current) at most occupies $\frac{1}{1000}$ sec. Under these circumstances the electrotonic incremental current does not make a clean entrance, either when the galvanometer electrodes are applied to the nerve under isoelectric conditions, or on leading off from longitudinal and transverse sections; the contacts always interfere with either the phasic current of action or the negative variation. The diminution of the nerve current observed in the last case, even without the rheotome, on tetanising with descending currents, must always—with adequate approximation of the leading-off and exciting tract—be due to the negative variation and the katelectrotonic incremental current. The rheotome, as it were, analyses this total effect into its single components, and determines the time-relations between the arrival of the excitatory wave, and of the electrotonic current, in each single stimulation. If the latter is already present at its full strength at the moment of closing the polarising current, the galvanometer deflection must obviously begin from that point, and increase steadily in proportion with the shifting of the rheotome from zero (*i.e.* the position at which the opening of the galvanometer circuit occurs simultaneously with the closure of the constant current) to that position at which closure of the polarising current coincides with that of the nerve circuit. This never occurred in Bernstein's experiment; on the contrary, after closure of the polarising current, there was a definite and measurable period before any effects appeared on the galvanometer. Let *SO* (Fig. 211) be the time-abscissa, *S* the closure, *O* the opening of the battery current, *Sy* the height of the "resting nerve current," then the entire process of katelectrotonic alteration that accompanies each single stimulus in the tract led off, is expressed by the curve *ngskte*. The galvanic expression of the excitation, which would otherwise produce a closure twitch, is first a fugitive negative variation, temporarily of the opposite sign (absolutely negative) to the nerve current in the given case. It is only much later, at *k*, that the negative variation due to the slowly rising katelectrotonic current commences. It occasionally outlasts the opening of the polarising current, and then disappears rapidly. The end of the *kathodic closure wave* (as Bernstein terms the initial negative variation due to the closing

excitation) usually coincides with the beginning of the katelectrotonic variation, and is inseparable from it.

From these experiments, as well as from the earlier observations of Tschirjew, it would appear *that the entrance of the katelectrotonic current at the point of leading off does not coincide in time with the closure of the polarising current, and that the underlying alteration of the nerve diffuses more slowly than the wave of excitation which precedes it.* This separation of the two apices is only seen distinctly when the tract of nerve led off is sufficiently remote from the polarised tract, since both

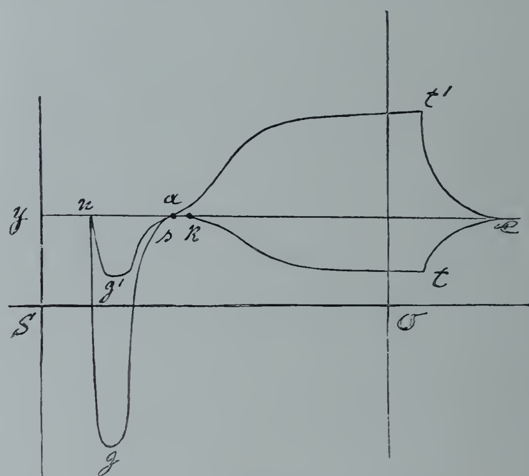


Fig. 211.

processes appear to begin simultaneously at the kathode, *i.e.* at the moment of closure, and, according to Bernstein's view, can only be separated after further propagation. The absolute rate at which the katelectrotonic alteration is transmitted can therefore hardly be determined exactly from such experiments. Bernstein estimates it at about 9–10 m. per sec. The development and diffusion of galvanic anelectrotonus is shown by the same method to be essentially similar, when the excitation by the rheotome is effected (by reason of the led-off transverse-section of the nerve) with ascending currents. Even with strong currents there is invariably a much smaller negative initial variation (excitatory wave) than with descending excitation, along with which there is a positive anelectrotonic deflection increasing

in proportion with the time (Fig. 211, *ng′at′e*). Once more, then, we find *propagation* of a certain alteration in the nerve, the absolute rapidity of which is best determined by leading off isoelectrically from two longitudinal points, since the negative variation then causes hardly any interference. Bernstein reckons this transmission at 6–13 m. per sec. In both phases of galvanic electrotonus, therefore, *certain alterations are propagated in the nerve from section to section, at a rate which, under all conditions, is considerably below that of the excitatory process.* This fact is obviously of great importance to the theory of electrotonic alterations.

None of these experiments, however, seem to have taken sufficient account of *the time-distribution of an- and katelectrotonic changes at any one point of the nerve, with a single closure.* The earlier experiments of du Bois-Reymond and Pflüger showed that with prolonged closure of the polarising current, both the state of depressed excitability, and the corresponding alterations in anelectrotonus at every point of the nerve, reach their maximum gradually, and then slowly decline again. Pflüger (32, p. 319) frequently found no trace of altered excitability, on rapidly exciting after a make twitch, the depression only setting in after 30 sec.–1 min.

"As the anelectrotonus swells up at any point, and reaches its maximum, so it declines again subsequently, and ebbs back towards the intrapolar tract, if the closure is protracted."

"The period of flow is less in proportion as the same current is more frequently closed, or is initially stronger, so that with very strong currents the anelectrotonus appears to break in suddenly."

According to du Bois-Reymond (30, p. 446, and 6, p. 255), this reaction is expressed, with reference to the apparently corresponding galvanic effects of anelectrotonus, by a curve of the form $a_0a_1a_2$ (Fig. 212); S being the moment of closure, t_1 the first reading of the galvanometer. The time-distribution of the *katelectrotonic* alterations during the passage of current is very different. The katelectrotonus at any point of the nerve invariably reaches its maximum (which is always lower than that of anelectrotonus under the same conditions) much earlier than the latter, and appears, at least as regards galvanic changes, to decline steadily from the commencement of the

observation (curve $k_0k_1k_2$). In regard to excitability, Pflüger (*l.c.* p. 349) determined a brief increase immediately after closure of the polarising current. It is clear, as was pointed out above, that the comparatively slow process of electrotonic alterations at any given point of the nerve, as well as the rapid diminution of intensity with increasing distance from the polarised part, must present great obstacles to an experimental determination of the rate of transmission. Galvanometric time-measurements more particularly break down (as Hermann pointed out, 35, p. 453) in this department, owing to our ignorance of the time-distribution of the initial stages of electrotonus. Even the foregoing experiments of Bernstein cannot therefore be regarded as decisive in this question of the transmission of the electrotonic state, the more so since they are opposed by other experiments which have not yet been contradicted. Valerius von Baranowsky and Carl Garré worked out a series of experiments under Hermann's direction upon the rate of diffusion of anelectrotonic alterations of excitability, partly on Grünhagen's principle as described above, and partly by a method of Hermann. A strong ascending current is led into the central end of a nerve connected with its muscle, while (with a Helmholtz's switch) another weaker constant current, also in an ascending direction, is closed as a test stimulus. Then, after ascertaining that the polarising current *per se* gives only opening and no closure twitches, while the weaker test current infallibly excites at closure, and on comparing the magnitude of this closing twitch with and without simultaneous closure of the polarising current, it will be found that in the last case, even where the two tracts of nerve are at a long distance from each other, the test stimulus will be ineffective, or will discharge a weaker make twitch than before. The fact that the interval between the closure of the two currents was in these experiments something under 0·0001 sec., gives a value for the diffusion of anelectrotonus, which at a distance of 16·5 mm. between the two tracts of nerve is in any case greater than 10,000 × 16·5,

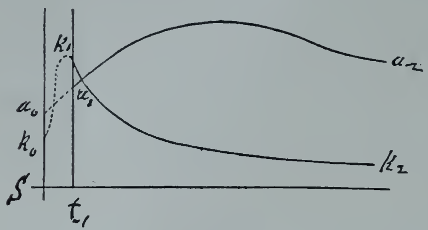


Fig. 212.

i.e. more than 165 m. Further experiments undertaken with Hermann's fall rheotome on Tschirjew's principle showed beyond doubt that the anelectrotonic depression of excitability is present at a point of the nerve 10 mm. distant, at the moment of closing the polarising current. The same must be assumed for the katelectrotonic rise of excitability, as well as for the galvanic expression of electrotonus. These experiments imply that the alterations are not propagated, like excitation, as a wave from section to section, but begin simultaneously at all points, at closure of the polarising current. These diametrically opposite opinions have not yet been reconciled, but it must be admitted that the last experiments of Hermann and his pupils are open to no well-founded objection, while the results of Bernstein's rheotome experiment are not, for reasons stated above, perfectly free from ambiguity.

2. *In Non-medullated Nerve*

A series of facts which are of great importance for the recognition of the true nature and characteristics of the electrotonic alterations in medullated nerve may be observed on certain nonliving (dead) conductors of a particular kind, and also upon *non-medullated nerve.* As regards the latter, it has already been pointed out that the appearance of the true, typical, extrapolar electrotonus is correlated with certain structural peculiarities of medullated nerve-fibres, more particularly the presence and integrity of the medullary sheath. This point must now be examined in detail. Among the few suitable objects of experiment we have—in addition to the olfactory nerve of the pike, as first employed by Kühne, and the unfortunately over-susceptible nerves of the crayfish (lobster) claw—in the larger examples of our native species of *Anodonta,* long unbranched non-medullated nerves, which extend from the two anterior to the posterior ganglia, and present a high capacity of resistance (Biedermann). As regards the electromotive properties of these fine nerve-fibres (which, if taken together, are not nearly as thick as the frog's sciatic), it has already been stated that the demarcation current is unusually vigorous, as in the pike's olfactorius.

If it is led off with unpolarisable electrodes to a sensitive galvanometer, while a battery current of 1–2 Dan. is passed into

the other end of a horizontally-stretched pair of nerves, there will, after compensation of the demarcation current, be (as described above) a more or less considerable deflection of the magnet at each closure of the exciting circuit, in the direction of a diminution (negative variation) of the nerve current, the magnitude of which depends essentially upon the direction of the polarising current. It is invariably greater when the current is flowing towards the leading-off end (3). We shall term this the descending, and its contrary the ascending direction of current.

The fact that the deflection in the two cases is homodromous, but unequal in magnitude, as well as its independence of distance between the led-off and polarised tracts, leaves no doubt that these are not pure electrotonic manifestations, but are complicated by the sequelæ of *excitation* of the nerve by current. The time-relations of the negative variation are remarkably different, according as the exciting current is ascending or descending. In the latter case it declines slowly during closure, in the former with great rapidity. If the polarised part of the nerve is at maximal distance from the leading-off tract, the negative variation at closure is, as a rule, the sole effect of excitation with either direction of current. If the intermediate tract is reduced, a *positive* deflection regularly succeeds the initial negative variation with ascending direction of current, its development and character being essentially conditioned by the ratio of its magnitude to that of the previous negative variation. Where this is large, the entrance of the positive after-effect is delayed after closure, and it increases more slowly during the passage of the current. An increasing acceleration of the deflection, or distinct swelling of the positive effect to its maximum, may often be observed, after which the magnet rests at its new position of equilibrium as long as the current is passing. The maximum of the positive variation invariably corresponds with a higher intensity of current than is required by the initial negative variation. Regarding the latter as an effect of closing excitation, it is significant that it becomes weaker in proportion as the intensity of the current increases, and finally disappears altogether (according to the third stage of the law of contraction). Under these conditions closure either produces no visible effect, where the distance between the exciting tract and the end led off is too

great to allow of a genuine positive variation, or (in other cases) the latter alone may appear, when the initial negative effect is often indicated by a distinct delay in the commencement of the positive variation. The different mode of action of ascending and descending currents also appears characteristically on breaking the circuit. With the descending break there is rarely any distinct augmentation of the negative deflection that is present during closure (in consequence of the opening excitation from the anode); for the most part there is no clear effect, or merely a slight delay in the return swing of the magnet. With ascending direction of current the negative "opening variation" is much more frequent and regular.

If these facts are compared with Bernstein's rheotome experiments on medullated frog's nerve, as above, a certain analogy can hardly be disputed.

Setting aside, in the first instance, the phenomena relating to "electrotonus," there is in the two cases a marked negative deflection immediately after closure of the descending polarising current, which from its whole character must undoubtedly be regarded as the galvanic expression of the make excitation. It is not surprising that this should be a rapid variation in frog preparations, a persistent modification in non-medullated molluscan nerve, seeing that indirect excitation of crayfish muscle by the constant current is, as a rule, sufficient to produce closure tetanus (*supra*). The closure of a not immoderate ascending current further produces in both cases a weaker but equally negative variation, which must, like the former, be referred to the closing excitation, and only fails with strong currents (third stage of the law of contraction). At a certain medium distance from the polarised tract there is in this case in molluscan nerve a positive deflection, immediately after the initial negative effect, which slowly increases during closure, exactly as was determined by Bernstein under similar conditions for frog's nerve. The graphic representation of this reaction (Fig. 211) may, with slight modifications, serve to express the consequences of ascending current in molluscan nerve on leading off from transverse and longitudinal sections, at not too great a distance from the polarising current. Owing, however, to the time-differences in the respective excitatory manifestations, the effects which in the former case require the application of the repeating-method for their analysis, are here directly obvious with

a single closure of the polarising current. From this it appears that non-medullated nerve also exhibits an alteration initiated at the anode of a polarising current, and connected with a development of positive potential, which spreads with diminishing intensity over a certain region beyond the poles, and is more widely diffused in proportion with the strength of the polarising current.

We cannot hesitate to compare this alteration (which is only expressed galvanically) with the "anelectrotonus" of medullated nerve, seeing that there is a fundamental conformity between them. It is therefore the more remarkable that there should be *no sign of alteration in non-medullated molluscan nerve comparable with the (galvanic) katelectrotonus of medullated nerve.* This is most apparent in experiments in which the galvanometer electrodes are isoelectrically arranged upon the nerve. With a descending polarising current there is then, as a rule, no effect; the magnet remains absolutely at rest at and during the closure of the exciting circuit, even when the galvanometer tract is only a few millimetres distant from the part excited. This shows that there is no spread of the polarising current by current-escape of any kind, in the preparation in question, beyond the region immediately traversed. The effects at and during closure of an ascending current, under similar conditions, are therefore the more striking. If the galvanometer electrodes (at uniform distance) are brought gradually nearer to the anode of the polarising current, there is invariably an increasing deflection in the sense of a rapidly augmenting anelectrotonus, which may reach considerable proportions while still comparatively remote from the anode.

The magnitude of these positive effects of the ascending current is determined not merely by its intensity, but also most essentially by the excitability of the preparation. The effects are always more distinct and more vigorous in proportion with the vitality of the nerve.

At a given position of the galvanometer electrodes, the magnitude of the positive deflection increases with augmentation of the ascending current only within a comparatively narrow range, and there is no approximate proportion between the two. The effect is generally maximal with the full current from two Daniell cells, while further rise of current intensity produces only an inconspicuous increase of deflection (Biedermann). This is true

both of the pronounced effects that obtain near the exciting tract, and also of the weaker and weakest effects at more remote parts. Seeing that the alterations of the nerve, fundamental to the homodromous incremental current below the ascending exciting current, require an incomparably longer period for their development than the initiation and transmission of excitation, the duration of closure of the constant current is an indispensable factor in the positive effect in question. Immediately after making the ascending current, or at the close of the negative variation, the scale passes beyond the zero-point in the positive direction, and moves towards the acme of the deflection, at first slowly and then more rapidly, until it reaches its limits after a closure of 5–6 sec. The nearer the galvanometer electrodes are brought to the exciting tract, the greater will be the positive effects, and the more marked this gradual swelling of the incremental current (homodromous with the exciting current), its strength remaining constant during further extension of closure. When—as is usual on leading off from the transverse end of the nerve—the variation is diphasic, *i.e.* first negative and then positive, the first phase nearly always predominates where the intermediate tract is of any length, and a moderate ascending current is employed. In this case, owing to the slow decline of the negative phase, a much longer closure is required before the gradually appearing and weak positive effect can be detected, than in a nerve with less distance between the galvanometer and exciting tracts, where the positive effect, as a rule, far outweighs the negative, or alone makes its appearance. In order to determine with certainty to what distance from the anode the effect extends, it is advisable to exclude the interference of the negative deflection, either by using very strong currents *ab initio*, or by killing the upper part of the exciting tract, and thus making closure excitation from the kathode impossible. In such a case, both with transverse leading off, and along the continuity of the nerve, there will only be a monophasic positive deflection, while, if the limit to which the alteration from the anode extends be exceeded, all perceptible effects upon the galvanometer will fail, at and during the closure of an ascending current. The rapid increment of effect on bringing the galvanometer electrodes nearer the exciting tract may thus be demonstrated with great distinctness.

As regards the interpretation of these electromotive effects beneath the anode of the ascending current, there cannot well—since no diffusion of the polarising current can be demonstrated on the side of the kathode—be any such in the vicinity of the anode either: the differences of potential developing along the nerve under the influence of current must therefore be referred to a physiological alteration of its state, transmitted apart from any presumable diffusion of current from the anode. This modification must undergo a marked decrement, otherwise it would be difficult to explain why there should sometimes be a mere trace of positive action at a distance from the anode, while vigorous deflections appear in the course of the nerve under uniform conditions. Nor is this the only point in which the positive alteration starting from the anode differs from the excitation discharged at the kathode, which is transmitted with a smaller decrement and apparently at much greater velocity; it further persists during the passage of the current at almost undiminished strength, or even increases, and only subsides rapidly on opening the exciting circuit.

Recent experiments of v. Uexküll (37) show that cephalopod nerves (*Eledone moschata*) react like those of *Anodonta*, in so far, at least, as regards failure of any conspicuous electrotonus.

3. *In Cooled and Etherised Medullated Nerve*

Biedermann (38) subsequently obtained effects from medullated frog nerve, under certain conditions, analogous with those described above for non-medullated nerve. These chiefly refer to alterations of electromotivity under the influence of the constant current, at maximal distance from the exciting tract, and with minimal currents. Usually, under these conditions, the single closure of an ascending or descending current, with transverse lead-off, gives at most a trace of effect as a negative variation of the demarcation current. But if, with preparations of cooled frogs (where the nerves frequently react tetanically to the weakest excitation), the galvanometer contacts are applied, at a small distance apart, to one end of the nerve, and the exciting electrodes (as far off as possible) to the other end, a very weak descending battery current being used as stimulus,—then the conditions for the

appearance of electrotonic action in the ordinary sense are most unfavourable, and any negative variation of the nerve current observed under such conditions may presumably be referred to persistent excitation from the kathode. Other data are also of great importance, theoretically, to this point.

In the first place, the magnitude of the initial deflection is independent both of intensity of exciting current, and also, within certain limits, of length of intermediate tract. The maximum effect usually appears with very weak currents, and it is immaterial whether a fraction of the current from a single cell or the full current of several cells is employed as excitant—the effect may indeed be less in the last case than with weaker currents. Nor, with uniform intensity of current, can the effect be increased by bringing the exciting electrodes nearer to the galvanometer tract (up to a certain limit). If, on the other hand, the intermediate tract is shortened by gradually shifting the galvanometer electrodes away from the transverse end of the nerve, with unaltered position of the exciting electrodes, a diminution of the negative variation is regularly observed at first with descending direction of current, amounting under some conditions to its complete disappearance (cf. Table I. *infra*).

If the galvanometer electrodes are approximated to the kathode beyond a certain point, a new series of homodromous (negative) deflections will appear, which, both as regards character during passage of current, and intensity, are quite distinct from the first series, and in all respects exhibit the same characteristics as those generally accepted as the signs of the electrotonic incremental current. These are, in first degree, dependence on strength of exciting current, and strikingly rapid increase of effect with approximation to the exciting tract. During the closure of the excitatory circuit these deflections either remain constant, or exhibit a gradual diminution, never amounting to disappearance.

The following tables illustrate this reaction. Both sciatic nerves of a very sensitive (cold) frog (*R. esculenta*) were simultaneously excited at their central end. NS = magnitude of deflection produced by the demarcation current; RW, the rheochord resistance; ZS, the length of the intermediate tract; SR, the direction of current. The sign > indicates the diminution of the deflection during passage of the current.

Much stronger negative deflections have frequently been

observed, under similar conditions, with both descending and ascending closure, in the nerves of cooled frogs, on keeping them for 12–24 hours before the experiment, with the skinned legs to which they are connected, in 0·6 % NaCl at room temperature.

TABLE I.

NS.	1 Daniell.	*ZS.*	*SR.*	Size of Deflection.		Remarks.
				Make.	Break.	
130 degrees	$RW=10$ cm.	40 mm.	↓	−9 > −2	+2	The longitudinal and transverse sections of the nerve were laid across the galvanometer electrodes. Length of galvanometer and exciting tracts = 10 mm. in each case.
			↑	−1 + 6	−3	
55 ,,	...	30 ,,	↓	− 6 > −2	+4	
			↑	+10 > +4	−2	
20 ,,	...	22 ,,	↓	−1	+3	
			↑	+16	−3	
20 ,,	...	19 ,,	↓	0	+2	*ZS* was gradually shortened by bringing the galvanometer electrodes nearer the excited tract.
			↑	+25	−4	
35 ,,	...	11 ,,	↓	−17	+3	
			↑	+40	−7	
100 ,,	...	40 ,,	↓	−2	+2	
			↑	+21	−2	

The gradually increasing concentration of the saline, from evaporation, seems here to increase the previous inclination of the nerve to tetanus, on exciting it with the constant current, as appears directly from observation of the muscle connected with it, which falls at closure of both descending and ascending currents into prolonged and vigorous tetanus. The galvanometer effects under the same conditions as before are proportionately stronger, and negative deflections of 15–20 degrees with descending, 4–7 degrees with ascending closure, are not infrequent, on leading off from the lower (transverse) end of such a pair of nerves. The diminution of effect on shortening the intermediate tract, by moving the galvanometer contacts away from the cross-section, is therefore all the more striking.

If deflections in the direction of katelectrotonic variations are accordingly perceptible at a greater distance from the kathode, only in the case of an initial P.D. between the contacts, then in uninjured, isoelectric frogs' nerve, at maximal distance

from the exciting tract, there will be absence of an- and katelectrotonic reaction, corresponding essentially with the electrotonic manifestations throughout the *entire* extrapolar tract of non-medullated molluscan nerve, and characterised above all by failure of genuine katelectrotonus.

If the sciatic nerve of a cold frog is prepared, together with the leg connected with it, and led off from two points as near as possible to the muscle (the exciting electrodes being as before—at the central end), then if there is no marked difference of potential the closure of a descending current will have no perceptible effect, even when it is of considerable intensity. This is also the case when the intermediate tract is shortened by shifting the galvanometer electrodes up to the bifurcation of the branch to the muscles of the thigh.

These statements imply that there is no considerable difference of potential within the unbranched part of the nerve. If the distance between the galvanometer and exciting tracts is reduced beyond a certain point, there will of course be katelectrotonic action here as in all medullated nerve, which will increase rapidly on shortening the intermediate tract, and essentially depends upon the intensity of the current. We shall return later to the character of the anelectrotonic manifestations in uninjured nerve, and need only state here that they can be demonstrated at maximal distance from the exciting tract (with ascending currents), and increase steadily on shortening the intermediate portion.

This is illustrated by Tables II. and III., which relate to highly excitable preparations of *R. esculenta*. The indications are the same as in the previous series.

If we first consider the electromotive alterations on the side of the kathode only, the extrapolar tract of the nerve is seen to fall, with sufficient length, into two sections, in which the electromotive effects that appear at and during the closure of a constant current originate (notwithstanding their similarity of direction) in fundamentally different causes. At maximal distance from the effective pole, distinct effects of katelectrotonus appear only when a current of rest is present, and occur more especially in nerves that are predisposed to tetanus. These effects diminish—irrespective of the shortening of the intermediate tract—with the diminution of P.D., when the galvanometer electrodes are shifted back from the cross-section, while much

more pronounced, but homodromous, electromotive alterations appear—under all circumstances, and independent of the excitability of the preparation, or of the pre-existence of a rest current—in the vicinity of the exciting tract, under the influence of the current. These increase rapidly with further shortening of the intermediate tract. The striking independence of the first-named, weaker effects in regard to current intensity (they may even decline in magnitude as the intensity of the current increases), and length of intermediate tract, makes it hardly doubtful that this is not ordinary electrotonus, but an effect of excitation.

The reaction of non-medullated molluscan nerve, in which true katelectrotonus seems to be altogether absent, is therefore comparable —under similar conditions—only with that tract of medullated nerve which is most remote from the part excited.

The electromotive alterations in medullated nerve below an ascending current exhibit several marked differences from the corresponding effects on the kathodic side, irrespective of the opposite direction of the deflections on the galvanometer.

On leading off from the peripheral end of a sensitive cooled nerve with an artificial section (it is usual to take two juxtaposed sciatics), and passing a weak ascending current through the central cut-end (1 Dan. $RW = 10–20$ cm.), there is invariably a positive variation of the (compensated) current of rest on closing the exciting circuit (cf. Table I.); this variation averages 5–15 degrees of the scale, and in most cases exceeds the corresponding effect of the descending current under similar conditions (Biedermann). It is altogether independent of the presence or absence of a demarcation current (an important point), and is present at almost equal strength in the perfectly uninjured and isoelectric nerve also (Tables II. and III.).

Table II.

Rana esculenta (cooled frog). Nerve with dependent leg.

NS.	Strength of Current.	*ZS.*	*SR.*	Size of Deflection.		Remarks.
				Make.	Break.	
0	1 Dan.	28 mm.	↓ ↑	0 +6>2	0 −2	The first lead-off was effected close to the point where the nerve enters the muscle. Length of galvanometer tract and exciting tract = 10 mm. respectively. *ZS* was shortened by bringing the galvanometer electrodes nearer the exciting tract. Each descending closure produced vigorous tetanus of the leg.
,,	2 ,,	28 ,,	↓ ↑	0 +4>2	0 −1	
,,	3 ,,	28 ,,	↓ ↑	0 +3>0	0 0	
,,	1 ,,	19 ,,	↓ ↑	Trace − +12>3	0 −3	
,,	2 ,,	19 ,,	↓ ↑	− 1 +12	0 −2	
,,	2 ,,	15 ,,	↓ ↑	− 2 +21	0 −2	

Table III.

R. temporaria (cooled frog). Sciatic with connected leg.

NS.	Strength of Current.	*ZS.*	*SR.*	Size of Deflection.		Remarks.
				Make.	Break.	
0 degrees	2 Dan.	32	↓ ↑	0 +6>2	0 −1	Method of experiment as above.
4 ,,	,,	25	↓ ↑	− 1 +11>3	0 −1	
0 ,,	,,	17	↓ ↑	− 2 +20>8	0 −2	
10 ,,	,,	11	↓ ↑	−13 +34	0 −4	

The only difference is the appearance in the first case of a more or less definite negative initial swing, often indicated only by the somewhat retarded entrance of the positive variation.

It is only in rare cases (when the ascending current produces

a strong closure tetanus) that there is a deflection of more than 1–2 degrees of the scale for the negative fore-swing. The positive effect quickly reaches its maximum, and at once declines again (sometimes even to zero).

On opening the exciting circuit there is usually a negative deflection, the magnitude of which depends essentially upon the duration of the previous passage of current; this declines slowly.

If the galvanometer electrodes are approximated (at unaltered distance) to the exciting tract, the intermediate portion of nerve being thereby shortened, the deflections caused by closure of the ascending current are rapidly augmented, independent of any pre-existing P.D., and soon exceed the negative variation produced with the same position of the leading-off electrodes by closure of the descending current.

The negative fore-swing which is generally present, or at least indicated, in the transverse lead-off is nearly always absent in leading off from the continuity of the nerve, so that mono-phasic, positive variations alone ensue, the magnitude of which diminishes the less during closure, in proportion as the distance between galvanometer and exciting tract is reduced. There is even a perceptible increase in the vicinity of the anode during closure. On opening the exciting circuit, there is usually a more or less pronounced heterodromous (negative) effect, with longitudinal as with transverse lead-off. This is at all events the rule in the vicinity of the exciting tract. At more distant points the appearance or failure of a negative opening variation seems, like the negative closure effect, to be conditioned essentially by the existence of a P.D. between the two contacts. The experimental tables quoted above contain evidence for all that has been said with regard to the galvanic alterations of the extrapolar region of the nerve, on the side of the anode.

The interpretation of these facts—relative to manifestations of negativity at make and break of the ascending current—can hardly be doubtful. The agreement with the corresponding phenomena in non-medullated molluscan nerve is here so striking that the same explanation, as the consequence of closing or opening excitation, is obvious. The frequent absence of the negative initial swing with ascending stimulation of medullated nerve, and its insignificance when present, is hardly surprising, when we remember that the effect depends, on the one hand, upon a

definite state of excitability (not always present in the same degree) in the cooled nerve, while on the other a pronounced closure tetanus with ascending direction of current is usually under these conditions of experiment exceptional; and further, the subsequent and much stronger positive effect soon defeats the initial heterodromous action. It is thus intelligible that the latter should disappear, or be present as a trace only, on shifting the galvanometer electrodes away from the transverse end of the nerve, and thereby rendering the essential conditions of its appearance still more unfavourable. Lastly, it can hardly be necessary to state that the application of strong ascending constant currents may obstruct the negative fore-swing, as well as the transmission of the closure excitation; it is, moreover, absent in isoelectric leads from the uninjured nerve, as, under all conditions, in preparations of warmed frogs.

We have already noted that Engelmann found a marked negative variation in the demarcation current of medullated frog's nerve on opening the battery current, provided the excitation took place under conditions in which a tetanic opening excitation might be expected.

As such, for instance, must be reckoned adequate strength and duration of the ascending exciting current, but most of all the disposition of the nerve to persistent excitation so frequently alluded to. Under favourable circumstances the negative opening effect on leading off from the transverse end of the nerve is not inferior in magnitude to the negative closure effect with descending excitation.

No definite conclusion as to the nature of the positive anelectrotonic closure effects can be deduced from the above experiments, since these exhibit along the whole extrapolar anodic portion of the nerve, a reaction essentially similar to that of non-medullated molluscan nerve, unless it be reckoned as a distinction that they appear in the former with weaker currents, and at a much greater distance from the part of the nerve traversed by the current. Since, as has been shown, the anelectrotonic alterations in non-medullated nerve can scarcely be explained otherwise than by a *physiological* change of state transmitted from the anode, it seems highly probable that a similar process occurs likewise when medullated nerve is traversed by current on the side of the

anode. On the other hand, the presence of an extrapolar katelectrotonus, homodromous with the alterations undoubtedly transmitted by conduction, leads us in the last case to conjecture that the galvanic anelectrotonus of medullated nerve may also, as it were, arise from two components—one, a *physiological* change of state transmitted, as in non-medullated nerve, from the anode, the other, a galvanic alteration, peculiar to medullated nerve, and corresponding with katelectrotonus proper, the purely *physical* origin of which has still to be discussed. We should thus anticipate that "physiological anelectrotonus" would appear in greatest integrity at maximal distance from the exciting tract, while in the vicinity of the anode it is complicated by other homodromous local alterations of the nerve, due to specific diffusion of the polarising current. This is also indicated in the fact, as above stated, that anelectrotonic effects far exceed the katelectrotonic in intensity and range, which is easily explained in view of the relations obtaining in non-medullated nerve. It is, however, desirable to bring forward further arguments, and, if possible, evidence, for such a separation between *physical* and *physiological electrotonus.* In one direction such evidence is offered by experiments on medullated nerve, in ether or chloroform narcosis, *where all changes transmitted by conduction would seem to be definitely excluded.*

From these experiments (for method cf. Biedermann, 38) it appears that *all electromotive alterations of the nerve, that may otherwise be observed at points remote from the tract through which current is flowing, disappear shortly after the commencement of etherisation* (5–10 min.). This applies both to the negative variation on closing the descending constant current, and to the positive effects with an ascending current. The ordinary negative variation, moreover, fails when the nerve is tetanised, showing that conductivity is really abolished (thus giving additional evidence *contra* Boruttau's theory of the negative variation, as above). Seeing that treatment with ether cannot fundamentally alter the physical and chemical properties of a nerve (as shown on the one hand by the constancy of P.D. between transverse and longitudinal sections, on the other by the rapid restoration of all normal vital properties of the nerve at the close of narcosis), the presumed double character of electrotonus becomes highly probable. It is proved, *i.e.*, to depend not merely

on the preservation of normal structural conditions in the nerve, but also, fundamentally, upon its conductivity.

Moreover, it can be shown that at a time when no trace of electrotonic action is demonstrable during ether narcosis at a distance from the exciting tract, there are strong and regular electrotonic currents in its immediate vicinity, and the reaction of these under prolonged etherisation is of great interest.

Normally there is without exception a marked difference in the strength of electromotive action on the side of the anode and of the kathode respectively, which is most distinct under the action of weak and medium battery currents. It follows that katelectrotonic deflections often fail altogether, or appear only as a trace at a distance from the exciting tract, while on reversing the current anelectrotonus may appear in its full strength, other conditions being uniform. Even in the vicinity of the exciting tract the difference between kat- and anelectrotonic deflections is considerable, the latter being often more than double.

This reaction is completely altered with progressive etherisation, i.e. the anelectrotonic deflections rapidly diminish at uniform excitation, while the katelectrotonic effect remains at first unaltered, or may even increase slightly. Subsequently there is always a point at which the kat- and anelectrotonic deflections are completely equalised, in respect of magnitude as well as of time-distribution, and this persists whatever the strength of current. It should also be remarked that with increasing current intensity the increment of deflection is approximately proportional in the later stages of ether narcosis. If the narcosis is sufficiently protracted, the katelectrotonic effect will also be modified in course of time (as would be anticipated), but the increasing diminution of the deflections will then keep pace with the simultaneous diminution of anelectrotonus.

If the narcosis is interrupted only when all trace of electrotonic action has disappeared, there is no recovery of the normal vital properties of the nerve; it is then, anatomically and physiologically, dead—the medullary sheath of the single fibres exhibiting the familiar clefts by which dead nerve is characterised. But if the preparation is removed earlier—directly after the heterodromous electrotonic deflections have been equalised—from the action of the ether, and placed in a moist chamber, recovery will at once set in, as evidenced by a rapid *increase in the magnitude of the anelectrotonic deflections, with constancy of*

katelectrotonic effect. Under favourable circumstances, vigorous preparations that have been cautiously narcotised will completely recover their normal properties, including that of conductivity in the nerve; in other cases there is, on the contrary, a perceptible loss (as expressed, *e.g.* in preparations of cooled frogs, by the frequent suppression of the negative variation of the nerve current described above as the galvanic expression of the make or break persistent excitation, at the close of narcosis—so that the nerve reacts precisely like a preparation from a warmed frog). With tetanising induction currents also there is frequently a visible and permanent diminution of the negative variation.

The figures contained in the following table will illustrate these facts: they refer to deflections observed under the same experimental conditions as the former series. *NS* = strength of the nerve current; *E*, number of (Daniell) cells; *ZS*, length of the intermediate tract; *SR*, direction of current.

	NS.	*E.*	*ZS.*	*SR.*	Deflection.		Remarks.
					Make.	Break.	
Single sciatic nerve from *Rana temporaria* (cooled frog).	0	1	10 mm.	↓	-25	+3	Before commencement of narcosis; length of galvanometer, exciting, and intermediate tracts, all 10 mm. The galvanometer electrodes are placed along the continuity of the nerve, and the exciting electrodes at the central end.
				↑	+46	-5	
	,,	2	,,	↓	-48	+2	
				↑	+73	-6	
	,,	3	,,	↓	-60	+2	
				↑	+96	-7	
	..	1	,,	↓	-30	0	After 12 minutes' action of ether.
				↑	+30	0	
	,,	2	,,	↓	-53	0	
				↑	+54	0	
	,,	3	,,	↓	-66	0	
				↑	+68	0	
	,,	1	,,	↓	-24	0	After 10 more min.
				↑	+24	0	
	,,	2	,,	↓	-40	0	
				↑	+41	0	
	,,	3	,,	↓	-60	0	
				↑	+60	0	
	,,	1	,,	↓	-24	0	10 min. after cessation of ether effect.
				↑	+37	0	

	NS.	*E.*	*ZS.*	*SR.*	Deflection.		Remarks.
					Make.	Break.	
Single sciatic nerve from *Rana temporaria* (cooled frog).	0	1	10 mm.	↓ ↑	−24 +42	0 −2	After 10 more min.
	12	1	9 mm.	↓ ↑	−75 +120	+4 −9	9 hrs. 55 min. immediately after commencement of ether effect. Length of galvanometer, exciting, and intermediate tracts, each 9 mm. Position of electrodes as in preceding experiment.
	,,	1	,,	↓ ↑	−80 +78	0 −5	10 hrs.
	,,	1	,,	↓ ↑	−73 +73	0 −5	10 hrs. 5 min.
	,,	1	,,	↓ ↑	−60 +60	0 −3	10 hrs. 12 min.
	10	1	,,	↓ ↑	−45 +46	0 0	10 hrs. 17 min.
	6	1	,,	↓ ↑	−30 +30	0 0	10 hrs. 25 min.
	,,	1	,,	↓ ↑	−17 +17	0 0	10 hrs. 33 min.
	5	1	,,	↓ ↑	−10 +10	0 0	10 hrs. 40 min.
	,,	2	,,	↓ ↑	−20 +20	0 0	10 hrs. 41 min.
	,,	3	,,	↓ ↑	−30 +30	0 0	10 hrs. 42 min.

If the above facts prove the existence of physiological changes of state, *i.e.* such as are transmitted from the poles—comparable throughout with electrotonus—they would seem to indicate a satisfactory explanation of the hitherto irreconcilable experiments of Bernstein, as well as of Hermann and his pupils. We have already pointed out that with regard to anelectrotonus the galvanometric effects in non-medullated nerve agree in every particular with the results of Bernstein's rheotome method on medullated frog's nerve. This is intelligible if it be admitted that, at the given distance between galvanometer and exciting tracts, the galvanic manifestations of excitation and of transmitted physiological electrotonus alone take effect; while the experiments

of Grünhagen and Hermann relate essentially to the consequences of *physical* anelectrotonus, the development of which, at different points of the nerve, is governed by quite a different law. Wundt's communications may possibly find an explanation from the same point of view. Under any circumstances, however, further investigation is required, in order to make a decisive judgment possible. Above all, it is legitimate to ask whether the katelectrotonus of medullated fibres (which appears to fail altogether in non-medullated nerve) may not also mask a "physiological component," as is certainly implied by Bernstein's experiments.

4. *In Polarisable Schemata*

We must now enter more particularly into the nature of "*physical electrotonus*," as exhibited in medullated nerve, during

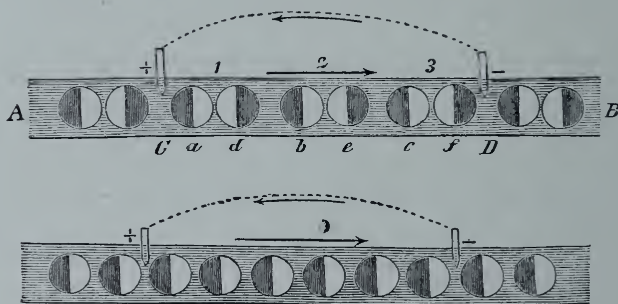


Fig. 213.

ether narcosis. Du Bois-Reymond attempted, from the standpoint of his molecular theory, to explain the whole of the galvanic manifestations of electrotonus by a directive influence of the polarising current upon the electromotive molecules of the nerve, which is not confined to the tract directly traversed, but extends more or less widely beyond it. If the nerve is conceived as constructed of peripolar molecules, each consisting of two *dipolar* halves (Fig. 213), the exciting (polarising) current, which is passed through one portion of the nerve, induces a homodromous incremental current in the *entire* nerve,—the electrically heterogeneous particles being arranged after the pattern of Volta's pile, the positive zones directed to the side towards which the current is flowing in the nerve, the negative zones, on the contrary,

to that from which it is coming—as in Grotthuss' theory of electrolysis. Du Bois-Reymond further assumes that this disposition in the direction of the current is not confined to the intrapolar tract, but extends in a diminishing degree to the extrapolar regions also, by which he explains the electrotonic incremental current. Since this interpretation stands and falls with the theory of pre-existing electromotive force in the nerve, which may now be regarded as disproven, we need not enter upon it in detail; and may turn to those experiments by which Matteucci, in 1863, indicated the true physical explanation of galvanic electrotonus (39). He found regular differences of potential in stretched metal wires (platinum) soaked in a conducting fluid, when any part of the wire was traversed by a constant current. At every point of the extrapolar region there was between each pair of points led off to the galvanometer a current homodromous with

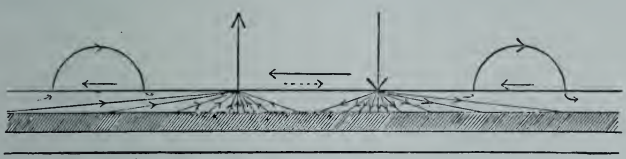


Fig. 214.

the primary (polarising) current, which was weaker in proportion as the point tested was more remote from the polarising tract.

Later on, the same phenomenon was thoroughly investigated by Hermann (39), who gave a complete theoretical explanation of it; showing it to be due, not—as Matteucci at first thought—to the consequences of spread (by diffusion) of the electrolysis occurring at the electrodes, but to a special case of polarisation ("*secondary polarisation*"). If a current is led into the moist sheath of a wire (Fig. 214) at two points, it depends, as Hermann showed, essentially upon the polarisability or unpolarisability of the combination how far the current will diffuse in the sheath of the metallic core. Matteucci stated that an amalgamated zinc wire, of which the sheath is moistened with zinc sulphate, gives no extrapolar differences of potential; and this was confirmed by Hermann. It is, in fact, easy to see that the current, under these conditions, will enter or leave the metal core at the actual electrodes and their immediate vicinity only, since the lines of current rapidly diminish in intensity, with increasing length, owing to the

augmented resistance. But if polarisation occurs at the point at which the lines of current pass from the fluid into the metal, and if there is in consequence such a marked "resistance" that the resistance due to unequal length of the lines of current is practically out of consideration, there is evidently nothing to prevent a wider diffusion of the current in the moist sheath along the core (Hermann).

As is obvious from the accompanying schema, a branch current must flow in every extrapolar leading-off circuit, at whatever point it is applied, in the direction of the polarising current (Fig. 214). The following observations of Hermann (39, v. p.

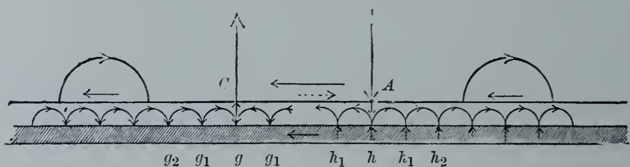


FIG. 215.

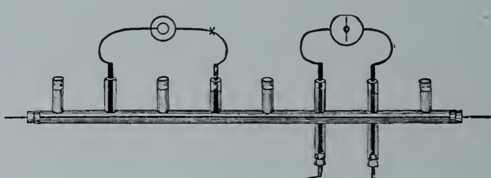


FIG. 216.

270) point to the same result. "In Fig. 215 the lines Ah and Cg show the path that would inevitably be taken by the current if there were no polarisation, in view of the thinness of the moist sheath and good conductivity of the metal core, in order to pass from the electrode points A and C to the core. If polarisation occurs at h and g, the metal (*e.g.* platinum in dilute sulphuric acid) would be charged with hydrogen at h, with oxygen at g. The platinum point h, which is charged with hydrogen, would then be electrically active towards the uncharged points near it h_1h_1, and currents would be generated in the moist sheath in the direction shown in the figure. These currents give off hydrogen at h_1h_1, oxygen at h, but in a quantity insufficient to neutralise the fresh hydrogen which is constantly being deposited by the current. The charged points h_1 are now electromotive to their uncharged neighbours h_2, fresh currents h_1h_2 arise which

again charge h_2 with hydrogen, and so on. The whole region round A is, however—so soon as a stationary condition has been established—charged (in a degree that diminishes with the distance) with hydrogen, that round C with oxygen. The currents that arise from these charges, and at the same time maintain them, can be detected in a leading-off circuit," as indicated above (Hermann).

For the more exact investigation of these phenomena, which are important to the theory of electrotonus, Hermann subsequently employed a model, in which the moist sheath was replaced by a free fluid (saturated zinc sulphate). This circulated in a glass tube (Fig. 216) with lateral openings, through which he passed a platinum wire. Amalgamated zinc wires served as the leading-in and leading-off electrodes. Apart from the facts quoted above, this experiment showed that every interruption of the wire (core-conductor), or of the liquid sheath, between the polarised and led-off parts, hindered the production of the extra-polar currents, which, for the rest, are proportional with the polarising current. They coincide with the electrotonic incremental current of medullated nerve, in so far that, with a given distance between the two tracts, their intensity increases with the length of area traversed (with uniform intensity of polarising current). The currents are further present at the moment of closure, and where the combination employed (*e.g.* platinum in zinc sulphate or sulphuric acid) is polarisable on both sides, are of equal strength at anode and kathode. On the other hand, the extrapolar currents on the kathodic side fail altogether, or appear only in the immediate vicinity of the pole, when the combination polarises on one side (the anode) only—*e.g.* zinc wire in H_2SO_4 or NaCl, copper wire in H_2SO_4 or $ZnSO_4$. Lastly, as in nerve, so in the core-model, the extrapolar incremental current fails altogether with transverse direction of current.

In the year 1883 Hermann discovered on a core-model (platinum in zinc sulphate), 2 metres long,—on passing in frequent, brief, constant currents of uniform direction, with Bernstein's rheotome—that, with a great distance between the polarised and led-off parts, the electrotonic currents sometimes began, or at any rate attained their maximum, only after the polarising current had been opened, which obviously points to an undulatory character of the corresponding galvanic processes. With a shorter distance between exciting and galvanometer tracts, the maximum of homo-

dromous, electromotive activity occurs at the end of the closure of the polarising current. Between the two leading-off electrodes, again (as in the phasic currents of action), there are two successive, opposite, and unequal phases of current, the first and stronger of which is homodromous with, the second on the other hand heterodromous to, the polarising current. This last phase does not here imply that the undulatory process moving forward with a rapidity of 20-65 metres per sec.—which on reaching the first leading-off electrode produces the first phase—gives rise to an opposite phase at the second contact (when it is simultaneously extinguished or greatly diminished at the first); but it is due to a heterodromous current arising at break of the polarising current, in the intrapolar tract of the core-conductor. "Shortly expressed, the second phase is nothing else than the comparatively retarded state into which the core-conductor is thrown by polarisation, in consequence of the rapid succession of momentary closures of the polarising current. The first phase, however, is the undulatory action of each single momentary closure, superposed upon this condition. It appears in complete integrity, when the two opposite polarisations of the wire core do not neutralise each other, or when one polarisation only is present, so that a bipolar current is impossible" (Hermann).

While Hermann is very cautious in accepting the possible bearings of these remarkable but theoretically insufficiently-explained phenomena upon the transmission of excitation in the nerve, and admits that there may be only plausible analogies, Boruttau (20) has recently adopted the extreme physical standpoint. He finds that, on leading in the alternating currents of an induction apparatus to a core composed of platinum or palladium wire in 0·6 per cent saline, by means of a rheotome, galvanic undulations are manifested, due to the rapid transmission (over 100 metres per sec.) of a *negative* phase to a considerable distance, and corresponding throughout with the phasic currents of action (*inter alia* as regards effect of temperature upon rate of transmission). As we have stated, he views the negative variation also as no more than an undulatory katelectrotonus. By employing very long core-models, consisting of many glass tubes placed together, by which the distance between traversed and led-off tracts could be increased to 4 metres, Boruttau observed the undulatory transmission of negativity, and *this alone*, with great

distinctness. On passing a constant current there is at the kathode only, on closing the current, at the anode on breaking it, "an effect, albeit brief and inconspicuous, in the direction of negativity of the proximal electrode." "This momentary negative effect is much more visible when single induction shocks are sent into the 'exciting tract' by a key. A brief negative effect corresponds with each such shock, *independent of its direction.*" Alternating currents produce negativity of the proximal electrode, which lasts as long as the "tetanisation." "Analysis by the differential rheotome also shows that a wave of negativity (*i.e.* katelectrotonus) is transmitted at these distances," it being a matter of indifference whether short, frequent battery currents, or induction shocks, are led through the exciting tract by the rheotome. "Both cases exhibit the wave of negativity spreading over the tract led off, in two phases, so that the proximal electrode is first negative and then positive to the distal contact."

Such complete identification of the negativity which is the concomitant of excitation, with the katelectrotonic wave, must be protested against, in spite of the many striking analogies between these phenomena in the core-model, and the galvanic reaction of medullated nerve traversed by the current. The objections which we hold to be conclusive against such a point of view are, in the first place, the appearance of analogous galvanic manifestations in electrical excitation of the most diverse "irritable" tissues, the structure of which in no way justifies us in assuming that they are core-conductors in the same sense as medullated nerve; further, the fact that etherised medullated nerves, in which physical "fixed polarisation" appears after, as well as previously, exhibit no trace of *transmitted* activity; and lastly, and above all, the fact that the galvanic manifestations of excitation appear equally in all appropriate objects *with other than electrical stimulation.* Boruttau, indeed, does not hesitate to refer once more to the properties of the core-conductor. He sees an analogue to the mechanical excitation of nerve and its galvanic consequences in the sudden rupture of the wire inside the moist sheath, after previously filing it at a given point, since he then observed in every case "with great precision," on leading off from a remote tract, "a comparatively conspicuous momentary appearance of current, or charge, followed by an immediate return to the previous state of rest." Without disputing these experimental data, no

one who has accepted the point of view that *living* animal or vegetable cells are alone excitable, could subscribe to the conclusions deduced from them. This is another example of the danger of generalising from observations on any *one* object, and of criticising vital manifestations from a one-sided physical point of view, without regard to differences of structure.

Without denying that further investigation may perhaps bring to light other analogies between the conduction of excitation on the one hand, and that of the undulatory electrotonus in the core-model on the other, it must be borne in mind that excitation and conductivity of excitation may be observed in objects, and under conditions, where Boruttau's physical assumptions are certainly not present.

Even for "*fixed polarisation*," however, it is questionable whether the persistent electrotonic currents that appear in the immediate vicinity of the area traversed in medullated nerve can be explained entirely on Hermann's principle of interpretation, although they are no doubt partly physical in origin. That structural constitution of the medullated fibres which here comes more especially (and perhaps solely) under consideration, *i.e.* the investment of the axis-cylinder with the medullary sheath, exhibits *prima facie* few characteristics integral to the original core-model of metal and fluid. In the first place, there is the enormous difference of conductivity between moist sheath and metal core. Any such marked disparity in conductivity between axis-cylinder and medullary sheath is obviously excluded *ab initio*; it may, indeed, be asked whether any perceptible difference exists. A second question is, whether any polarisation at all is present at the interface of these two elementary constituents of medullated nerve, and if so, whether such a polarisation at the surface of two electrolytes can, as regards its effect upon current diffusion, be compared with that taking place at the junction between metal and fluid?

With regard to the first point, Hermann long ago gave experimental proof that the very considerable difference between longitudinal and transverse resistance in the nerve is essentially to be referred to an E.M.F., heterodromous to the current and due to polarisation. With transverse passage of current this seems to occur mainly at the boundary between neurilemma (sheath of Schwann) and medullary sheath, so that with Hermann we must

regard as core-substance, not merely the axis-cylinder, but the "entire protoplasmic contents of the tube"; as sheath, not merely the medullary sheath, but also "the neurilemma, and the interstitial connective tissue."

Hermann brought parallel frogs' nerves, placed together, between two quadratic glass plates, and determined the resistance by Wheatstone's method, passing the current once longitudinally, and once transversely, to the direction of the fibres. "The transverse resistance was five times as great as the longitudinal resistance; the former is about twelve and a half million, the latter only two and a half million times as great as that of mercury."

If the existence of surface polarisation is accepted on the analogy of the core-model for medullated nerve, it must further be asked whether the intensity of such polarisation at the interface of the two electrolytes is sufficient to account for the observed diffusion of current in the nerve. From a purely theoretical standpoint this cannot be disputed. In view, however, of the intensity of the electrotonic effects, we should practically be compelled, with Hermann (40), to recognise in the nerve an "unparalleled" force of surface polarisation, since "the polarisation at the interface of normal fluids (which is very weak as compared with the metal-fluid combinations) could only, in consequence of the resistance, induce a very feeble diffusion, which would be altogether masked by the experimental errors."

Nevertheless, experimental combinations of moist conductors have been found to give exceptionally strong effects in the sense of a pronounced and regular electrotonus; this reaction, however, must be referred less to surface polarisation in Hermann's sense than to a peculiar mode of current diffusion, according to a theory advanced by Grünhagen (41) and Hering (24). Hering employs a simple model for "physical electrotonus," which is admirably suited to all demonstrations, *i.e.* the long stem of the pipe-grass, without internodes, which is first soaked in water, and then filled just before the experiment with concentrated saline. The feelers and bones of the crayfish, preserved in alcohol, and saturated before the experiment with 0·6 per cent saline, are no less convenient.

The striking similarity of the resulting electrotonic manifestations with those observed under the same conditions in etherised

nerve, extends not merely to equality of an- and katelectrotonic deflections, but also to the more or less approximate proportion which exists at a given position of leading-in and galvanometer electrodes, between the magnitude of effect produced and intensity of the polarising current (38). An essential characteristic of "electrotonic" currents, as opposed to ordinary current escape, is presented by the fact that the direction of the extrapolar current led off is determined by the position of the galvanometer

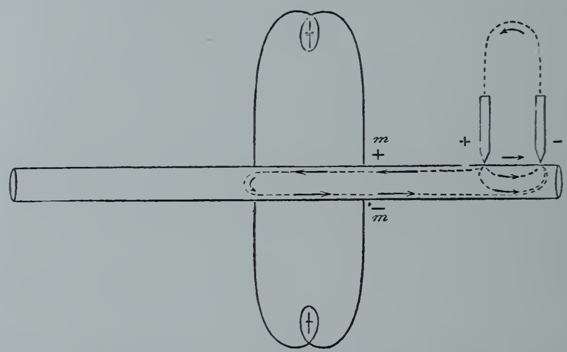


FIG. 217.—Schema of current diffusion in an ordinary conductor partially traversed by current.

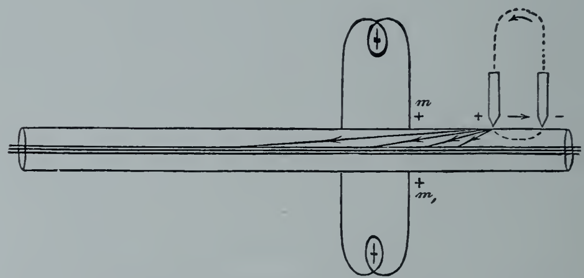


FIG. 218.—Schema of current diffusion in a "core-model." (Grünhagen.)

current. This is shown by the accompanying schema (Fig. 217), where it is seen that the extrapolar branches of current led off from opposite sides of the conductor must necessarily be heterodromous. On the other hand, this does not occur either in the nerve or in any of the models described above. *Whatever the position of the galvanometer electrodes, the current led off is invariably homodromous with the polarising current. The sole essential condition is that the axis of a moist conductor should contain a core of better conductivity than the sheath.* It is immaterial whether, as in

Matteucci's core-model, this is a *metal*, or, as in Hering's experiments, as well as in an analogous method of Grünhagen (42), and in certain combinations recently employed by Boruttau, a *fluid* conductor. According to Grünhagen (Fig. 218), we should imagine that in every combination of conductors on the plan of the accompanying schema (Fig. 218), "the branch currents running in the sheath take only one direction towards the better-conducting core, while the recurrent branches, on the contrary, are included within the better-conducting axis." "In consequence of this absorption of all recurrent diffusion-currents by the core-conductor, the sheath is free of them, and wherever the leading-off contacts of the galvanometer circuits are applied, whether at the side near, or opposite to, the leading-in electrodes, there will only be branch currents in the one direction, identical with that of the diverging lines of current as described above" (Grünhagen). If this view is accepted, the axis-cylinder should be a much better conductor than the medullary sheath, which, indeed, from the histo-chemical point of view, seems not improbable. The complete failure of any definite *physical* electrotonus in non-medullated nerve, and in muscle, would accordingly be determined by the absence of badly-conducting sheaths to the single elements; to which it must further be added that (as has been recently confirmed—Biedermann) electrotonic effects are also absent in cases where, as in many crustacean nerves, the solitary axis-cylinder is surrounded by well-developed stratified sheaths of connective tissue. The physico-chemical constitution of the medullary sheath appears, therefore, to be indispensable to current diffusion. In this connection there are some interesting experiments on the nerves of *Palæmon*, which, according to Retzius, contain medullated fibres, and thus differ completely from those of most other crustacea.

As the outcome of the preceding discussion, it must be admitted that there is in medullated nerve a diffusion, whether produced by "secondary polarisation" or by direct current escape, of the external current over the tract directly traversed, *i.e.* an electrotonus of *physical* origin, which is however complicated, as a rule, by homodromous *physiological* alterations of the nerve. From the physiological standpoint the chief interest lies in the alterations of the nerve, *i.e.* of its excitability, produced by the diffusion of the exciting current. In muscle, where the entrance

and exit of the current are confined essentially to the actual contacts and their immediate vicinity, the polar action of the current finds localised expression on the one hand as excitation, on the other as inhibition, only at the points at which it is initiated. But where, as in medullated nerve, the physiological anode or kathode (*i.e.* the region within which lines of current pass in and out of the excitable substance of the axis-cylinder) has any considerable extension, the same must of course hold good of all the consequences of excitation and inhibition. The spatial extension of physical electrotonus as the sum of all the changes directly produced by the electrical current is, in other words, masked by the spatial diffusion of anodic and kathodic points in the tissue traversed by the current. If it is thus a law for muscle as well as nerve that, within certain limits of current intensity and passage at the physiological kathode (*i.e.* at every point by which current leaves the excitable substance), there is during closure a condition of augmented "expectancy"—the contrary being the case at the physiological anode—we have in this a direct interpretation of the facts of intra- and extrapolar alterations of excitability, as diffused antagonistically from the poles in a polarised medullated nerve. This further explains the striking *rise of excitability in the vicinity of each artificial cross-section.* As in the case of an external current, the demarcation current of each medullated nerve-fibre will not merely equalise itself in the immediate proximity of the demarcation surface, but (again for the same reasons) will give off lines of current to a long distance from the cross-section, as indicated in the accompanying schema (Fig. 219); and these, escaping in all directions from the axis-cylinder, throw the latter into katelectrotonus with all its sequelæ, the intensity of the same of course declining rapidly with distance from the cross-section. The so-called weak longitudinal currents may therefore, as was first pointed out by Hermann (cf. Fig. 219), be regarded simply as the electrotonic spread of the demarcation current.

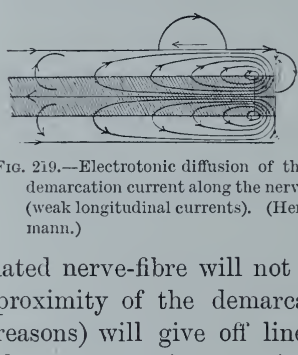


FIG. 219.—Electrotonic diffusion of the demarcation current along the nerve (weak longitudinal currents). (Hermann.)

Lastly, there is the fact already alluded to that, in electrical excitation of a medullated nerve that has undergone local morti-

fication, the physiological action of one pole may, as in muscle, be excluded, if a greater or less part of the intrapolar tract is killed, with as little injury as possible to histological structure. This, again, is simply explained by the spatial distribution of the points by which current leaves and enters, as well as the difference already pointed out between abterminal and atterminal induction currents, sent into the transverse end of a medullated nerve. The E.M.F. at the boundary of "altered" and non-altered nerve-substance is presumably very high, since there is a marked action from the deriving currents led off externally; so that the intensity of the branches of current, which are short-circuited in the proximity of an artificial transverse section of medullated nerve, by the substance of the sheath, must undoubtedly be very great, owing to the low resistance of their microscopic longitudinal path (Hermann).

VI. Secondary Electromotive Changes in Nerve following the Passage of a Current

As in muscle, so in medullated nerve, it was shown by du Bois-Reymond that every part traversed by a current of adequate strength exhibited regular electromotive action in a given direction when the circuit was broken. He referred the phenomena in both cases to "internal polarisation," since it appeared that an opposite (eventually homodromous) after-current could also be observed when the two leading-off electrodes to the galvanometer were situated between the exciting electrodes, within the intrapolar region. It has already been shown (I. p. 444) that this view is erroneous, at least as regards muscle. In the case of nerve the investigation is much more difficult, owing to the smaller intensity of effect, and still more from the electrotonic diffusion of the (polarising) exciting current. Nevertheless, it may be affirmed from all the observations made up to the present time that no real difference exists in regard to secondary electromotive phenomena, between nerve and muscle. Du Bois-Reymond obtained maximal negative effects after prolonged passage of comparatively weak currents, while maximal "positive polarisation" occurred after a brief closure of a strong battery (25–30 Groves !), (43). Hermann, who at first found no fundamental difference in the deflections, on sending current through a tract of nerve 40

mm. long (two frog's sciatics with the opposite ends in contact), when the leading-off tract was successively as near as possible to the anode, and then to the kathode, finally determined that "the homodromous after-phase of the current was regularly absent in nerve, as in muscle, when the physiological anode coincided with the artificial transverse section and was led off from there." Hence there is no doubt that the homodromous after-current ("positive polarisation") is to be viewed exclusively as the galvanic expression of the opening excitation.

The wide extrapolar diffusion of the polarising current in medullated nerve makes it desirable to test the reaction of the *extrapolar* after-current on breaking the circuit. The first investigation was made by Fick (44), who found that a heterodromous after-current appeared on both sides of the polarising current, and quickly vanished again. A little later on Hermann (45), followed by Fick, asserted that this occurred only on the side of the anode, while a current, homodromous with the polarising current, appeared beyond the kathode, its strength being always less than that of the anodic after-current. In regard to the latter, moreover, Hermann subsequently ascertained (46) that it was preceded by a brief variation, homodromous with the polarising current.

Hermann explained all these manifestations by the "polarisation" after-currents (which he carefully investigated on the "core-model"), in combination with the "irritative" after-currents due to polar manifestations of excitation, and especially to the opening excitation. We have already seen that these last are alone sufficient to account for all secondary electromotive effects in muscle, and the same is *a priori* probable for nerve also. Further investigation is, however, desirable before coming to a final decision. In any case, the extrapolar, anodic after-current (heterodromous to the polarising current) depends upon the negativity, which gradually diminishes from the pole outwards, and is the galvanic consequence of the opening excitation; while the homodromous, extrapolar, kathodic after-current may equally be defined as "irritative," if the negativity, which—as in muscle—again declines from the pole outwards, is viewed as the after-effect of the previous excitation, extending, of course, in a medullated nerve as far as there are points of exit for the lines of current.

We have farther to examine the reasons brought forward by Grützner and Tigerstedt (48) for their contention that certain forms, perhaps indeed all opening twitches, produced by negative polarisation currents are really closing twitches. In view of the above, it is evident that this current, when of adequate strength, may play the same part along the continuity of the nerve as the demarcation current at the transverse end, *i.e.* that it can eventually set up "false" opening twitches.

And, in fact, Peltier (who in 1836 was the first to observe negative polarisation in the limbs of frogs through which current was passing, and whose investigations formed the starting-point of du Bois-Reymond's labours in this direction) had already interpreted the opening twitch by the polarisation current. Du Bois-Reymond, however, stated against this view that "these charges, in order to induce a current through the nerve, required to all appearance a closed circuit, which condition was cancelled by opening it" (23, i. p. 381). Matteucci was also of Peltier's opinion, that the opening twitch could be explained by the (negative) polarisability of the nerve, without, however, adducing any cogent evidence (47).

As regards du Bois-Reymond's objections, their importance is lessened, since it has been established experimentally that the internal short-circuiting of a demarcation current that occurs both in muscle and in nerve is sufficient to discharge an "apparent" break twitch. Under the presumption of adequate intensity, the same phenomenon may be anticipated for the negative polarisation current produced by the exciting current, and it only remains to show experimentally that certain opening twitches may really come about as described above.

Grützner (*l.c.*) set up experiments with the view of determining whether there might not be different modes of appearance of the opening twitch, with indirect excitation of the muscle, according as the polarising heterodromous current is short-circuited at the moment of opening the exciting current by a good external shunt circuit, or, in the absence of such a shunt, short-circuits itself internally in the nerve. And there does actually seem, more particularly with metal electrodes, always to be a difference agreeing with the theory. The opening twitch, *i.e.*, appears much earlier (viz. with weaker exciting currents), or is more pronounced, in the presence of an external shunt for the polarisation current,

than when it is absent. Hermann has communicated similar experiments which he carried out in 1875-76, with the same result, but did not publish.

From these facts it appears that the polarising heterodromous current is, under the given conditions, implicated in the discharge of the opening twitch, although we must by no means conclude that it is invariably the sole factor. This conclusion seems, however, to Grützner and Tigerstedt to be justified, mainly by the fact that all those circumstances which are favourable to the appearance, or increase, of a negative polarisation current are also conducive to the appearance of the break twitch.

The normal, vigorous, and uninjured nerve is characterised (as was remarked above) by a certain resistance to excitation from the break of an electrical current, so that tolerably strong battery currents are required to discharge opening twitches after a brief closure. When, however, a break twitch has once been discharged by an adequate current, then even weak currents (that previously took effect at make only) will excite directly afterwards, provided that in both cases the same tract of nerve is traversed by the current. After a brief period of rest this excitatory effect disappears again completely. Grützner and Tigerstedt interpret this reaction to mean that the negative polarisation current, set up by the stronger current in the tract traversed, and gradually subsiding at break of the exciting current, disposes this tract during its passage to the discharge of "false" opening twitches, in which case the short-circuiting of the polarisation current can only (with the normal method of opening the exciting current) be internal, occurring within the nerve itself.

Tigerstedt arrived at the following results from his investigation of the time-relations of negative polarisation in frog's nerve, as well as its dependence upon intensity and duration of the exciting current:—

(i.) Within certain limits of current intensity the (negative) polarisation of the nerve is directly proportional to the strength of the exciting current.

(ii.) If the polarising current acts upon the nerve during an indefinite period, polarisation increases; it rises quickly at the beginning, then more slowly, reaching its maximum with extreme sluggishness.

(iii.) When the polarising current is opened, the polarisation rapidly reaches its climax, and then sinks again continuously; this fall occurs quickly at first, and afterwards more slowly, so that polarisation lasts for a long time after the opening of the polarising current, and only reaches its zero asymptotically.

The opening twitch agrees in all three points with the negative polarisation current. We have already referred to the fact that motor frogs' nerves are so altered by the action of dilute solutions of alkaline salts, or alcoholic salt solution, that at a given stage the weakest constant currents will discharge opening twitches, after quite brief closures, of the same character as the break twitch from a transverse section,—which alteration may be completely neutralised by washing out the foreign substances.

Tigerstedt finds that "the (negative) polarisability of the nerve also rises on treatment with alcoholic saline to 1·5 times its original height," and sees in this fact a further confirmation of the view that the opening twitch is the closure twitch of the negative polarisation current. Finally, Tigerstedt refers the earlier appearance of the break twitch on exciting the divided sciatic plexus, as compared with the excitation of peripheral points of the nerve (Biedermann and Grützner), to a more ready polarisability of those sections of the nerve. The demarcation current must, however, play the principal part.

In summing up these facts, it can hardly be doubtful that *certain* forms of opening twitch are to be interpreted as closure twitches from the negative polarisation current. Such sweeping generalisations as those formulated by Tigerstedt, and more recently by Hoorweg (49), which "refer the opening excitation and all phenomena that occur on opening the polarising current" to "the (negative) polarisation current, and in certain exceptional cases to the nerve-(muscle) current," are, however, quite unjustifiable. They are more especially contradicted by the fact that, as was pointed out by Hermann, break twitches also appear on merely diminishing the current (in negative variations of intensity), in which case there is usually no polarisation current, since the anode can never become kathode if the diminution is less than half.

There is yet another point of view from which it appears possible to approach the question of whether the electrotonic incremental current is due solely to physical current escape, or to

physiological alterations of the nervous substance. Something may be learned from the reaction of electrotonic currents on exciting the nerve, *i.e.* the current of action in electrotonised nerve. The first of these points was investigated by Bernstein (50).

He began by examining into the alterations of the negative variation of the demarcation current, when a tract of nerve is simultaneously traversed above or below the exciting tract by a constant current. If the latter is, in the first place, very weak, the polarising electrodes being also so remote from the transverse lead-off that any perceptible interference of electrotonic currents must be excluded, there will, when the exciting electrodes in connection with the secondary coil of an induction apparatus are placed between the polarised and led-off tracts of the nerve (are, *i.e.*, " infrapolar "), regularly be an augmentation of the negative variation with the descending, a diminution of it with the ascending, direction. The contrary effect occurs on exciting *above* the polarised region of the nerve.

These results obviously agree in the main with the electrotonic alterations of excitability as determined by Pflüger, since the galvanometer merely takes the place of the normal index of muscular excitation. But if the polarising electrodes are brought nearer to the led-off transverse section, so that the electrotonic differences of potential are at first weak, and subsequently augmented,—the demarcation current either diminishing (in the negative phase) or growing stronger (positive phase), according to the direction of the polarising current,—there will then, with infrapolar tetanising excitation, be a distinct decrement of the negative variation in the negative phase of electrotonus, produced by descending current; an increment, on the other hand, in the positive phase, with ascending current. In the first case the negative variation may, if the strength of the polarising current exceeds a certain limit, be reduced to 0, or even reversed in sign. The former invariably occurs when the demarcation current vanishes altogether in the negative phase. If, on the other hand, the current is reversed, the P.D. increases during excitation in the same direction. There is thus " a distinct dependence of the negative variation upon the strength and direction of the entering electrotonic phase. If the latter augments the nerve current, the negative variation increases also; when it diminishes it, the negative variation is also diminished, and

falls to zero, so soon as the led-off current disappears entirely in the negative phase. The variation consequent on excitation is therefore invariably negative to the initial sign of the nerve current." As Bernstein remarks, these results are easily explained on the assumption "that the current led off from the nerve in a state of electrotonus reacts like an ordinary nerve (demarcation) current. The weaker it is, the weaker is its negative variation, and *vice versa.* The two disappear together, just as the negative variation disappears on leading off from two symmetrical points of an unpolarised nerve, and reversal of the current reverses the sign of its variation also" (*l.c.* p. 622).

Bernstein established by further experiments (in which the excitation, whether suprapolar or otherwise, along the continuity of the nerve, was led off from two longitudinal contacts) that the electrotonic incremental currents give a precisely similar reaction on exciting medullated nerve to that of the ordinary demarcation current. This appears most plainly when the polarising and exciting electrodes are applied to either end of the longest nerve available, the lead-off being from two points of the intermediate tract. Since in this case the electrotonic alterations are not obliged to pass the point of excitation, nor the excitation the polarised tract, in order to reach the leading-off circuit, the effect of excitation on electrotonic currents may be investigated in its integrity. While Bernstein explains these observations by a diminution, consequent upon excitation, of the energy or activity of the supposed electromotive molecules, Hermann is led, by his interpretation of the galvanic manifestations in electrotonus, to refer these facts to alterations of intensity in the negative wave of excitation, during its passage through the nerve, when the latter is polarised. "It is indeed more pronounced at any point of the nerve, the more strongly positive and weakly negative the polarisation of the latter, *i.e.* it increases when it is becoming algebraically more positive, and diminishes when it advances upon more negative points" (Hermann's law of the "polarisation increment" of excitation).

VII. Theoretical

Although it is hardly possible at the present time to formulate any theory of electrical excitation that shall cover all its

manifestations, it still seems advisable, in view of the previous data, which are based upon a great number of single observations, to attempt to reach certain general standpoints whence a survey of the whole department shall become possible. In the present state of our knowledge it is obvious that this can only be the most general orientation, and we may perhaps say with justice that here, as in other departments of physiology, the final explanation is more remote than seemed probable at no very distant period. Du Bois-Reymond's brilliant discoveries roused a hope, amounting even to conviction in many minds, that the molecular theory—so acutely conceived and fraught with such weighty consequences—pointed to a real *physical* comprehension of all phenomena of nerve and muscle activity, although it was clear from the beginning that chemical processes played a no less important part. So strongly, however, had the first view obtained the ascendant, in consequence of the overpowering effect of the data arrived at in experimental physiology by purely physical methods, that there was no hesitation in finding a parallel between muscle and nerve, and dead, inorganic bodies. As against this there has of late been notable progress, most workers now insisting on the *chemical* aspects of vital function, or at least regarding these as equal with the physical processes. Du Bois-Reymond, indeed, subsequently defined the electromotive molecules, which he regarded as the constituents of nerve and muscle, as a definitely orientated crowd, with pronounced chemical activity, and Bernstein, to whom we shall return, took the same view. Nevertheless, in judging of the significance of this hypothetical molecular structure to vital processes, and more particularly to electromotive changes in the activity of nerve and muscle, stress was laid, not on the concomitant alterations of intra-molecular constitution, but on the physical change of place of each molecule. Du Bois-Reymond himself never attempted to apply his theory to the explanation of excitation *per se,* or its propagation from the seat of direct stimulation. He was contented to derive the correlative galvanic manifestations from it, and expressly warns us against considering the "pile-like" polarisation of the nerve, by which he accounts for electrotonus, to be identical with "the process which conditions movement and sensation" (23, p. 385). Notwithstanding this, there is no lack of conjectures which in this respect far outstrip those of the founder of the molecular theory; and it is interesting

(as well as characteristic of the physical considerations which till recently prevailed in physiology) to study the theories which were subsequently expressed as to the nature of electrical excitation in particular, from the starting-point of the molecular hypothesis. In vol. i. of Funke's excellent text-book (2nd ed. 1863) the following characteristic statement occurs on p. 859: "The exciting electrical current disposes the molecules of the nerve between the electrodes in a dipolar arrangement, on the system of the voltaic pile; the molecules which lie at the edge of the dipolar layer first produced by the electrical current attract those which lie beyond the electrodes, and are directed contrary to the exciting current. These again act upon the next inverted series, and so on, until all the molecules are arranged down to the end of the nerve like a pile. It follows that at the moment when electrotonus is produced in the tube of the nerve, a process of transmission takes place, analogous with the course of a wave along a trough filled with water. In this last case we learn from physics that there is a progressive displacement of the single particles of fluid, at a given rate, from the point at which the wave is excited to the end of the trough: in nerve there is a progressive displacement of the molecules from the excited spot to the two ends in succession, in consequence of the electrical action at a distance of each molecule upon its neighbours. The propagation of this molecular movement occurs like that of the wave of water, with comparatively low and measured velocity. A process of transmission corresponding in some degree with the negative wave occurs in the nerve-tube at the moment when electrotonus ceases. When the exciting current is interrupted, the molecules between the electrodes return by virtue of an unknown directive force to the peripolar arrangement; their directive action upon those external to them consequently disappears—the latter also return to the peripolar disposition, along with those succeeding to them, and so on to the end of the nerve. The attraction of the molecules at the close of electrotonus (opening of the current) is opposite in direction to that at its commencement; the direction of transmission is the same, analogously with the relations of the positive and negative wave of water. We have already seen that the beginning and end of electrotonus, the closure and opening of the exciting current, are accompanied by a twitch of the muscle connected with the nerve, *i.e.* that the muscle twitch due to the

arrival of excitation at the muscular end of the nerve occurs at the two moments in which the progressive change of position in the molecules of the nerve reaches the molecules of that end of the muscle. We have seen that a twitch of the muscle accompanies every sudden alteration of density in the exciting current; here too, as may easily be shown, the twitch which notifies the state of excitation coincides with a motion propagated in the nerve from molecule to molecule in succession till it reaches the muscle. The pile-like arrangement in electrotonus is not quite perfect, *i.e.* the molecules directed contrary to the direction of the pile are turned not quite at an angle of 180°, but only at fractions of the half-circle, of different magnitudes. The size of this revolution depends, apart from other conditions, upon the density of the exciting current. If this density is suddenly increased to a certain degree, then each molecule in order turns a fraction farther, as directed by its neighbour; conversely each molecule turns back a fraction on the momentary diminution of the current density. This progressive and partial revolution of the molecules already deflected out of the peripolar disposition is, like the original rotation at the beginning of electrotonus, accompanied by a twitch of the muscle; while no twitch occurs so long as the molecules are at rest, no matter whether they are peripolar or more or less dipolar in arrangement, or whether the rotation of the single molecules follows gradually at greater intervals, as is the case in gradual increase or decrease of current density. The more considerable the instantaneous rotation communicated from neighbour to neighbour, the greater will be the state of excitation expressed by the degree of the muscle twitch."

"A persistent and apparently constant state of excitation in the nerve is produced by a current interrupted at short intervals (either by homodromous or by alternating and heterodromous shocks): here we must picture each of these short currents as accompanied at its commencement and termination by movements of the molecules of the nerve, so that during electrical tetanisation the molecules undergo a rapid series of rotations in different directions. Under these circumstances, therefore, the transmitted movements of the electromotive molecules, and the excitatory condition, coincide in the electrically-excited nerve; neither is seen without the other, neither outlasts the other. The two must therefore be

intimately related, if they are not identical; *i.e. the transmitted state of excitation is constituted by the transmitted movement of the electromotive molecules.*"

The difficulties in the way of such a schematic and one-sided point of view, under even the most favourable instances of excitation by the electrical current (*e.g.* the fact of the rapid diminution of intensity of electrotonic action with distance from the point of excitation), have not prevented attempts to explain the mode of action of other stimuli on the same principle. Eckhardt, for instance, thought it possible to refer the effect of *chemical* excitation of the nerve to a transmitted change of position of the supposed molecules, starting from the erroneous presumption that the necessary condition of every non-electrical excitation is the momentary death of the excited part of the nerve. The destruction of the electromotive molecules in the part that has been killed, and consequent loss of their directive influence on their uninjured neighbours, causes these to take up new positions, and thus progressively alters the position of all the following molecules.

But even the simple molecular theory of electrical excitation, as set forth above, is shown to be wholly untenable, so soon as the law of the exclusively polar excitation of "excitable" substances is recognised as universally valid. In particular, the evidence brought forward by Pflüger to show that there are antagonistic changes of state, expressed in opposite alterations of excitabilty in the vicinity of the two poles of a constant current led through the nerve, as well as the further proof that excitation starts at closure from one electrode only (the kathode), at opening from the other (the anode), cannot, as is evident even from the standpoint of the molecular theory, be reconciled with the idea of complete identity between the progressive "pile-like" polarisation and excitation. For it is not conceivable that the molecule should change its position at closure at the kathode only, on opening, on the contrary, at the anode; much rather would every point of the whole tract traversed participate equally in the discharge of the excitatory process, since the primary changes of position of the molecules, according to du Bois' theory of electrotonus, occur equally between the two poles throughout the intrapolar area.

Without directly subscribing to du Bois-Reymond's molecular

theory, Pflüger (32) has very acutely tried to establish a view associated, on the one hand, with the idea of a molecular structure of the nervous substance, and illustrating its essential phenomena under the figure of physical alterations within the system, while, on the other, it is in line with all the experimental data known up to the present. We shall mainly refer to the lucid account which Funke (*Physiol.* 4th ed. i. p. 865 ff.) gives of Pflüger's theory. Pflüger starts with the presumption that there is in nerve—as, indeed, in all "excitable" substances—a combination of molecules "which constantly strives to enter into motion, but cannot, because there is an obstacle, a *molecular inhibition.* Since the molecular combinations of the system have a constant tendency to movement, there must be a constant force which drives them. But inasmuch as the molecules remain at rest, the force of inhibition must be equal and opposite to the former" (Pflüger, *l.c.* p. 478). In the resting condition of the nerve, the two forces of molecular energy and molecular inhibition are in equilibrium, the latter being maintained by given forces at a given position, which it instantly recovers when other forces working upon it have produced a temporary disturbance. Displacement of the elastic molecular inhibition in a double and opposite direction must further be possible, the conditions for discharge of energy being induced by the displacement in one of these directions, in such a way that more potential is converted into dynamic energy in proportion as inhibition is displaced in one direction, while displacement in the opposite direction, on the contrary, produces accumulation of potential energy.

Pflüger gives a graphic figure of the mechanism of discharge in any cross-section of the nerve. A cylinder bent at right angles (*ABC*, Fig. 220) carries on its horizontal limb *AB* a water-tight piston *D*, which is movable in the direction of the arrows *ab* and *cd*. A compressed spring fastened to the piston presses against it on one side, and impels it with a certain force in the direction *ab*. On the other side, the fluid poured into the vertical arm of the cylinder pushes against the piston, with the hydrostatic pressure corresponding with the height of the column of fluid in the vertical limb *BC*, and tends to push the piston in the direction *cd*. The piston will obviously come to rest in that position at which the tension of the spring, and the pressure of the column of fluid, are in equilibrium. Behind the piston

there is an opening *g* in the horizontal arm of the cylinder, which Pflüger conceives to be spiriform, its highest point lying next the piston. If the elasticity of the spring is increased, it presses more strongly upon the piston, pushes it farther from the opening *g*, and displaces the fluid in front of it, which then rises higher in the vertical limb, and there is increased hydrostatic pressure. If, on the other hand, the elasticity of the spring is diminished, the fluid displaces the piston in the opposite direction *cd*, and pushes it more or less away from the opening *g*, which is then reached by the fluid, which, on streaming out, acquires vital energy deriving from the height of fall. With this streaming out, the hydrostatic pressure diminishes, so that the force of the spring gradually pushes the piston back again over the opening and ends the discharge.

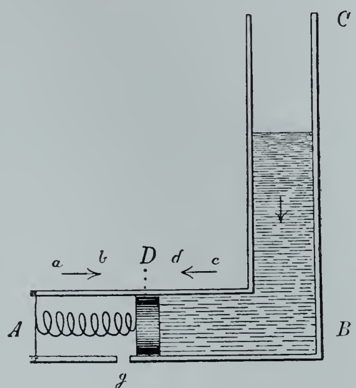


Fig. 220.

We have next to see how this schematic mechanism explains the reaction of the living transverse section of the nerve with respect to excitation, conductivity, and excitability, and, in the first place, the phenomena and laws of electrotonus. This explanation follows simply from the following hypothetical premiss as set out by Pflüger. The electrical current flowing through a portion of the nerve alters the force of molecular inhibition, and this alone, in a direct sense, with no immediate modification of potential energy. The effect of current on the inhibitory force is to increase it in the region of anelectrotonus, and diminish it in that of katelectrotonus, *i.e.* the elastic force of the piston-spring increases in all sections of the cylinder, which represent anelectrotonised sections of the nerve, and decreases in those that are katelectrotonised. Further, in the anelectrotonic region the inhibitory force, *i.e.* the piston *D*, is displaced in the direction of the arrow *ab*, whereby the potential energy, *i.e.* the height of the column of fluid at *BC*, increases, while in the katelectrotonic region, on the contrary, the piston is displaced in the direction *cd*, so that potential energy is indirectly diminished. A positive increment of inhibi-

tory force is therefore the indirect cause of a positive increment of potential, and, conversely, a negative increment of the one tends to negative increase of the other. On this assumption the depression of excitability in the anelectrotonised parts, and its rise in such as are katelectrotonised, is quite intelligible: the greater elastic force of the inhibitory spring in the anelectrotonic region involves a greater expenditure of force in order to push back the piston to the opening of the cylinder-sections, than in the normal state; the diminished energy of inhibition in the region of katelectrotonus involves less force. It is harder to explain, *first*, how with low intensity of polarising current an excitation generated at any transverse section can be transmitted through katelectrotonised as well as anelectrotonised tracts in the same way as through the nerve in the natural state (and, strictly speaking, this is not the case),—so that the stronger excitation discharged above an ascending current produces a more vigorous twitch than in the natural state, although it must be transmitted through the anelectrotonised parts, which, with direct excitation, give less response: *secondly*, how it is that at a considerable strength of polarising current the anelectrotonised parts lose their conductivity also. These difficulties were, however, surmounted by Pflüger. The conduction of excitation set up at any transverse section is effected by the expenditure of the dynamic energy discharged at the seat of stimulation upon the displacement of molecular inhibition in the next section, the energy thereby released in the second section displaces the molecular inhibition in the next, and so on. The molecular inhibitions are less easily displaced in the anelectrotonised parts in consequence of the increased elasticity of the spring, more easily displaced in the katelectrotonised parts, than under natural conditions. The fact of unaltered conductivity in *weak* electrotonus therefore indicates that in all conducting sections of the nerve, the magnitude of displacement of the molecular inhibitions depends entirely upon the amount of dynamic energy set free at the directly-excited transverse section, and is proportional with the same in every section, irrespective of whether the displacement of inhibitions is facilitated or hindered. This is only possible if, when excitation is transmitted from one section to the next, the total sum of dynamic energy released is not consumed in the displacement of molecular inhibition: such a proportional aliquot part only being required as

suffices for the extent of displacement involved by the strength of stimulus, viz. a larger proportion in the region of anelectrotonus, where displacement is less easy; a smaller amount in that of katelectrotonus, where it is facile. Pflüger illustrates this hypothesis by the figure of a wheel turning on a horizontal axis, its revolutions being aided or hindered by the greater or less pressure of a sliding spring. This wheel carries, at the peripheral end of a horizontal spoke, a laterally-projecting, horizontal paddle. A thin stream of water falls on this from above, and thus presses down the wheel, until the paddle is pushed out of reach of the stream of water. The proportion of the falling stream of water, *i.e.* of the dynamic energy available, required by this constant revolution of the wheel, is greater in proportion as the spring presses more heavily upon the wheel, and the latter therefore revolves less easily. The reason that the anelectrotonised parts lose their conductivity in pronounced electrotonus would accordingly be that, in consequence of the excessive rise of inhibitory energy, the total sum of active energy discharged by the stimulus is no longer adequate to bring about the corresponding displacement of molecular inhibition, just as, with undue pressure of a spring against the wheel, the whole column of water is inadequate to move the paddle, with the wheel, beyond its reach.

The fundamental law of electrical excitation at the poles, as laid down by Pflüger, whereby the commencement of katelectrotonus produces the closure twitch, the disappearance of anelectrotonus the opening twitch, is explained by himself as follows, upon this theory. The commencing anelectrotonus reinforces the inhibitory energy, and therefore displaces the piston *D* of the schema in the direction of the arrow *ab*, driving it away from the opening of the sluice; obviously no fluid can then escape from the opening *g*. On the contrary, the streaming out, *i.e.* the conversion of potential into active energy, is now even less possible than in the previous resting state of inhibition; it is therefore impossible that excitation should ensue from the entry of anelectrotonus. The opposite occurs at the region of the kathode. The commencing katelectrotonus diminishes inhibitory energy, weakens the elastic force of the piston spring, the piston is pushed by the overwhelming hydrostatic pressure in the direction of the arrow *cd*, the mouth by which the fluid escapes is freed,—in other words, there is a discharge of potential energy. If the energy lost in the discharge

is not replaced, the latter can only be instantaneous; for the outflow of fluid reduces the hydrostatic pressure in *BC*, the spring once more pushes the piston *D* over the opening; there could only be a momentary closure *twitch*. But if the potential energy given off is replaced, the discharge will also continue, like the outflow of fluid, provided always that fluid is poured into the vertical limb of the cylinder in the same quantity that flows out, *i.e.* there is closure *tetanus*. The opposite relations obtain on opening the current. At the moment of opening, the previous rise of inhibitory energy in the region of anelectrotonus returns to the normal; potential energy then, of course, predominates, displacing the inhibition in its own direction, *i.e.* in the line of the arrow *cd*. The retreating inhibitions, however, come to rest as little as a pendulum, on again reaching the equilibrium from which they were driven by the anelectrotonus. They go slightly beyond it, so that the mouth *g* is opened for a moment for the discharge of the fluid; this produces the opening twitch. It is obvious that no potential energy can be set in the katelectrotonised region, when, at the moment of opening the current, the reinforced elasticity of the spring displaces the inhibitions in the direction of the arrow *ab*, *i.e.* there can be no excitation. The hypothesis based on the phenomena of the law of contraction, to the effect that the closure of a given current excites more strongly than its opening, follows as the naturally corollary from Pflüger's theory of discharge; for, if at the closure of the current the inhibitions at the anode are as much displaced in the direction *ab* as they are at the kathode in the direction *cd*, then, at opening, the inhibitions in the anelectrotonised region are not displaced as far from the normal, in the direction *cd*, as the inhibitions in the region of katelectrotonus at closure, *i.e.* there cannot be the same discharge of potential energy. If a rapid succession of brief electrical currents is sent into the nerve, the apparently continuous *tetanic* excitation is due to the continuous alternating discharge of energy at anode and kathode, which persists as long as metabolism continues adequate between every shock to replace the energy dissipated in the last shock. The mechanics of the law of contraction are thus simply explained on Pflüger's hypothesis.

We have next to see whether it can account for the *after-effects* of the constant current, the so-called modifications of the nerve as above described. We have seen that a state of heightened

excitability (positive modification) appears, and slowly subsides, in the previously anelectrotonic portion of the nerve, on opening the current. Pflüger takes this to mean that the action of the constant current weakens the energy of molecular inhibition, which is highly probable, seeing that, according to his theory, the current acts during its passage upon the inhibitory forces, but not directly upon potential energy. The weakened inhibitory force left over at break must obviously present less resistance to the transformation of potential into active energy than it would on resuming the proportions normal to it before closure of the current; and this explains how the nerve that is depressed by current comes to be more excitable, *i.e.* apparently invigorated. The restitution of the normal inhibitory forces, as gradually brought about by metabolism, explains the subsidence of the positive modification. The brief negative modification that appears in the region of katelectrotonus after opening the current is explained by Pflüger as a momentary deficit of potential energy, and this again by the fact that katelectrotonus (*supra*) keeps the sluice permanently open, *i.e.* causes a continuous outflow of potential energy.

Lastly, with regard to the after-effects of the polarising current, manifested in a more or less prolonged discharge of potential energy, Pflüger has shown that the opening tetanus starts from the region of anelectrotonus; this indicates that there is, on opening the more sustained currents within the previously anelectrotonised tract, a persistent discharge of potential energy. If we represent this as the displacement of the piston by the reinforced spring, and assume that the column rises so much under the action of the water in A, that the piston is pushed back again to the spiral opening, there will be then a considerable accumulation of water at A. If the elasticity of the spring is suddenly depressed, the column of water will push the piston far back, and a greater quantity of water will flow for a longer time, until equilibrium is restored again. This process corresponds with the opening tetanus.

Pflüger's theory thus succeeds in presenting the main phenomena of electrical excitation of nerve under the figure of a complicated mechanical schema: it gives no real explanation of them. It seemed, however, advisable to give the theory in detail, seeing that it found wide acceptance. While Pflüger himself developed his hypothesis independently of du Bois-Reymond's molecular theory, Bernstein attempted later to establish a direct relation

between them (28, p. 52). The "molecular tension," *i.e.* the potential force inherent in each molecule, which "accumulates persistently in the process of nutrition," is identified by Bernstein with the electrical E.M.F. of du Bois-Reymond's peripolar molecules, as neutralised in excitation, with correlative movements of the molecules. "The tendency in the latter to neutralise their electrical E.M.F. is opposed by an inhibitory force (unknown to us in its intrinsic nature), which prevents any movement of the molecules in the resting state" (Pflüger's "molecular inhibition"). Whether this is the result of friction, of elasticity, or of both is uncertain; there is a play of forces "which tends to maintain the components of the molecules (*i.e.* the peripolar molecules formed of two dipolar bodies) in their natural position, and restores them to the same after each alteration." Any stimulus, of whatever kind, "disturbs the natural position of the molecules," whereby molecular inhibition is interrupted, and there is neutralisation of the electric potential. As regards electrical excitation in particular. Bernstein accounts for the reinforcement of molecular inhibition at the positive pole, and consequent decreased mobility of the molecules (diminished excitability), as well as the lowered inhibition and raised mobility (increased excitability) at the negative pole, by the attraction or repulsion exerted by the polarising electrodes upon the peripheral molecules next to them. The positive electrode fixes these, as it were, in their place, the negative zones being turned towards the pole, while the kathode, by repulsion of the same zone, renders them more mobile. This is why, at closure of the current, excitation proceeds from the kathode only. The molecules at the positive pole remain in their normal position; "at the negative pole, on the other hand, inhibition is weakened, the exciting energy preponderates and causes excitation." On opening the circuit, inhibition falls suddenly at the positive pole, and the increased potential energy of the molecules is now discharged, and induces excitation. Electrotonic alterations of excitability, and other phenomena, receive a similar interpretation.

The dictum long since expressed by du Bois-Reymond (*Untersuchungen*, II. i. p. 387), to the effect that *galvanic excitation is nothing more than the first stage of electrolysis in excitable tissues*, may still (though in a somewhat different sense) be accepted as the most apt theoretical definition of the

physiological action of current. It is singular that it should date from a time at which the law of polar excitation was still unknown, since the evidence of the latter again turns our thoughts, almost involuntarily, in the same direction. Von Bezold expresses himself directly in this sense at the close of his detailed investigation into the electrical excitation of nerve and muscle. In the fact that "the molecular process of excitation arises with such regularity at and during closure, and on opening the current, at a definite pole, and not in the whole extension of the tract through which the current is passing," he sees evidence that "*the excitatory action of the galvanic current is to be sought in the chemical effects produced by the current in the moist conductor which it traverses*" (*l.c.* p. 237). He recalls the antagonism of the polar alterations, and Kühne's remark that a tract of muscle traversed by current shows coagulation in the region of the anode, and corrosion at the kathode, as well as Jürgensen's experiments upon the cataphoric action of the current, and concludes from all these data that the excitatory process is nothing more than an effect of electrolysis due to current. "*Electrical excitation would, accordingly, be nothing else than a definite form of chemical stimulation*—the process, like that of the generation of hydrogen, occurring exclusively at the negative pole, during closure of the current" (*l.c.* p. 328). The arguments adduced (by von Bezold in particular) to show that the process of excitation is discharged at the kathode during the entire passage of the current, are obviously quite in line with this theory.

The greatest advances in the direction indicated came, however, from Hermann's electro-physiological researches, which most of all contributed to bringing forward the chemical side of function in all these vital phenomena, while the resolution with which he attacked du Bois-Reymond's molecular theory helped to remove one of the greatest hindrances to the fruitful development of general nerve and muscle physics. Hermann's *law of the current of action* (to the effect that each excited part is negative to parts that are less excited, or unexcited) forms, indeed, with the law of the exclusively polar action of electrotonic currents in excitable tissues, the basis of all modern opinion on the subject, and gives the key to the interpretation of a vast number of experimental data. Hering, again, like Hermann, has steadily maintained that all the processes in excitable living matter are, in

first degree, to be regarded as *chemical*, and that "the true chemical nature of vital processes must not be overlooked in their physical symptoms" (24, p. 59). Hering has developed upon the most general grounds, and, as it were, in final consequence of his physiology of the senses, a theory of the functions of living matter (more particularly under electrical excitation), which, though as yet little recognised, is really the most comprehensive expression of all the data relating to this department. By it he is able to derive and to explain all facts quite simply from a few fundamental postulates of metabolism. Hering starts with the proposition that, when a muscle or nerve is longitudinally traversed by current, the excitable substance is altered in an opposite sense at the physiological anode and kathode: more correctly, antagonistic alterations in the chemical state of the substance are set up at the two poles—since at all points by which current enters the uninjured living matter, the *assimilatory* process preponderates, and (to use Hering's expression, cf. p. 71 f.) effects an "allonomous ascending" alteration, while *dissimilation* (disintegration) prevails at the collective points of exit, inducing "allonomous descending" alteration. Every excitation, in the ordinary sense of the word, is undoubtedly characterised by the predominance of the dissimilatory process, it being immaterial whether this process is confined to its seat of origin, or propagated further by conduction. Under all circumstances, therefore, the physiological kathode is the seat of excitation lasting throughout the closure of the current, the *closing excitation*. Hering's account of the processes at the anode, developed as the corollary to his theory of visual sensation, is less obvious.

"Just as we may conceive of external stimuli which compel the living substance to vigorous dissimilation, so others are conceivable which enforce greater activity of assimilation. This increase of assimilation, which is no longer purely autonomous, and is not balanced by corresponding activity of dissimilation, modifies the living matter in a direction contrary to that described above as '*below par*,' and therefore to be denoted '*above par*.' At the close of such excitation the living matter is over-nourished; its disposition to assimilation is less than before, in ratio with the intensity and duration of stimulus, and the corresponding preponderance of allonomous assimilation over autonomous dissimilation—the disposition to dissimilation is pro-

portionately greater. Hence, at close of excitation, autonomous dissimilation preponderates over autonomous assimilation, and the living matter, owing to its gradual depreciation, returns to par" (*l.c.* p. 39). The effect of the anode upon muscle and nerve is, according to Hering, to be regarded as a similar assimilatory stimulus. If, *e.g.*, the living matter had previously been at par, and, therefore, in autonomous equilibrium between D and A, it rises above par at the point where the current enters. When the current ceases to flow, there is a corresponding autonomous down change at the point of entrance, which is the more rapid in proportion as the substance has risen above par during the previous "up" change. Thus, the point of entrance may become the starting-point of a second excitation ("*opening excitation*") spreading over the fibre. At the point of exit, on the contrary, there is an autonomous up change on breaking the current, provided this point has not been seriously injured by the previous action of the current, or, generally speaking, disturbed in its assimilatory conditions.

"Since a rapid allonomous 'down' change occurs during the passage of current, at the point of exit, this point is negative to the rest of the fibre (in so far as the latter is not in transmitted 'excitation'); while the point of entrance, in consequence of localised allonomous 'up' change, gives the opposite reaction. This causes an internal current in the fibre, opposed in direction to the led-in, foreign current. This internal current weakens the foreign current. It has been termed a 'polarisation current.' But inasmuch as it is a *physiological heterodromous current*, an intrinsic vital manifestation, it must be rigorously distinguished from those polarisation currents which are not properly physiological, since they do not arise from the up or down changes in the living substance that occur at the points where current enters or leaves it; for heterodromous currents may also appear, with artificial excitation, in dead tissues, or parts that are no longer intrinsically excitable in the still living organ.

"Given normal activity of living matter, an autonomous down change may, as we have seen, appear at the anode, on opening the foreign current—this point being now negative to the rest of the fibre, in so far as the latter is not undergoing progressive descending alteration; while the kathode becomes positive to the rest of the fibre, in virtue of an autonomous 'up' change. A

physiological current is thus developed in the fibre, in the same direction as the opened foreign current. This physiological current may be termed *homodromous,* in contradistinction to that previously defined as *heterodromous.* It appears the more certainly in proportion as the substance is more energetic ; and the less the vital processes are affected by the foreign current, the more rapidly will the allonomous alterations, induced by the latter (after-effect of excitation), disappear, and the opposite autonomous changes develop, when it is broken. The homodromous physiological current is more or less likely to be disturbed by complication with physical polarisation currents, heterodromous to the foreign current.

"If a foreign current is led through the central portion of a medullated nerve, the points by which it enters and leaves the excitable matter spread far beyond the contacts of the physical electrodes. So far as these points of entrance and exit extend, there is correlatively with the distribution of the lines of current a purely *physical* 'an- and katelectrotonus,' as may be demonstrated, *e.g.* on a dry hollow stalk of grass without internodes, or on a bundle of the same stalks that have been lying for some time in distilled water, or weak alcohol, and are then moistened externally, and saturated internally, with salt solution. From this wide distribution in the excitable substance (axis-cylinder) of the nerve, of the collective points at which the foreign current enters and leaves it—*i.e.* the *physiological* anode and kathode proper—those 'up' and 'down' changes develop respectively in the nerve, which are fundamental to physiological *electrotonus* (Pflüger). Both down and up change may, after closure of the foreign current, be transmitted along the nerve beyond the tracts altered in a kathodic (negative) or anodic (positive) sense by the direct action of the current, so that fugitive alterations may occur even at very remote parts of the fibre, as expressed in its electromotive reactions. On breaking the foreign current, an opposite alteration takes place at the points of entrance and exit, with corresponding changes in the living matter, *i.e.* autonomous descending or ascending alterations respectively. The two points have interchanged their parts ; the ascending alteration, characteristic of physiological anelectrotonus, now appears at the former kathode, the descending alteration, significant of physiological katelectrotonus, at the former anode.

"In non-medullated nerve, *e.g.* olfactorius, and in muscle, where the excitable substance, unlike medullated nerve, has no imperfectly-conducting sheath, the characteristic diffusion of entrance and exit points is wanting. The electrical phenomena which depend upon this diffusion (due, in the first place, to relations of conductivity), together with the physiological *local* consequences of the same, are accordingly absent. On the other hand, the phenomena caused by *transmission* of the ascending or descending alteration induced at the anode or kathode of the foreign current are more or less plainly exhibited both in non-medullated nerve and in muscle-fibre.

"If a tract of nerve has been traversed for some time by a foreign current, and the current is then reversed, the excitable matter at the point of exit (*i.e.* former point of entrance) will be absolutely, or relatively, above par, and thus has a greater disposition to 'down' change; the current accordingly produces a more rapid descending alteration than would otherwise be the case (Volta's alternative).

"Muscle-fibre, as compared with nerve-fibre, has the great advantage of expressing the excitation due to descending alteration, by change of form of the part affected; while a foreign current can, moreover, enter and leave at the natural ends of the fibres. In the latter case, the allonomous change which occurs on closure at the point of exit is, in the first instance, transmitted along the fibre, but when the closure twitch has expired, it persists only near the point of exit during closure (*persistent kathodic contraction*), and steadily decreases. Meantime, the autonomous up change continues at the point of entrance, and may raise the living matter considerably above par, given adequate strength and duration of current. At break there will accordingly be an autonomous down change, which, if sufficiently rapid, may produce an *opening twitch*, or *persistent opening contraction*, near the point of entrance. Even when this autonomous down change is so weak that no visible alteration of form can be detected in the muscle, it may express itself in the physiological homodromous current (*supra*), which appears on connecting the anodic end with, *e.g.*, the centre of the muscle.

"Autonomous ascending alteration cannot always be demonstrated at the point of exit, on breaking the internal current, because the autonomous assimilation of the living matter in excised

muscle is too slow and inadequate a process—as was pointed out above. Yet in favourable cases the autonomous up change is exhibited in a physiological homodromous current, that makes its appearance at break, if the now kathodic end of the muscle is put in circuit with the centre of the muscle.

"The fact that muscle-, like nerve-fibre, fails to react to transverse passage of current, obviously signifies that living matter is not intrinsically the same living continuum in the transverse as in the longitudinal direction; as appears from optical polarisation phenomena, and from the relations of elasticity. The failure in reaction is perhaps due to the fact that the antagonistic points at which the current leaves and enters are too closely approximated in the structural elements traversed at right angles by the current.

"When a strong foreign current has been flowing longitudinally through an uninjured muscle for so long that the persistent kathodic contraction has already expired, the persistent anodic contraction (*supra*) will appear when the current is broken, and may extend over a large tract of the muscle, and last for a considerable period. If the current is then closed again, it will act as an *inhibitory stimulus* on the contracted muscle, which at once relaxes completely. The anodic stimulus of the foreign current, which tends to upward alteration in the substance, now works against the rapid autonomous down change that prevailed after break at the point of entrance, and substitutes an up change. Owing, however, to the previous exhaustive allonomous descending alteration, there is not inevitably a new closure contraction at the point of exit.

"Just as the persistent opening contraction of a muscle may be inhibited by renewed closure of the current, another contraction depending on autonomous down change may be inhibited by the action of an anodic current. If, just at the beginning of systole, a stronger current is sent in through one brush-electrode, the point of which rests upon the frog's heart (exposed with uninterrupted circulation), while the other electrode forms contact with, *e.g.*, the skin of the throat, a more or less extended diastole of the heart-wall, starting from the point where the current enters, will make its appearance. The commencing autonomous down change is immediately converted, by the anodic action of the current, into an allonomous up change, and the relaxed part of the cardiac wall swells out freely in consequence of blood-pressure. The

contrary effect appears when current leaves the heart by the brush-electrode. If closure occurs at the beginning of the general diastole, a new systole will at once appear at the point of exit (*kathodic closure contraction*).

"If the current is left undisturbed for some time in this last direction, and is then opened during a general diastole, the wall of the heart near the brush-electrode will not take part in the ensuing systole, owing to the marked autonomous up change; it remains diastolically relaxed, and the systolic pressure of the blood causes the relaxed point to swell out considerably. This is the *kathodic opening inhibition*, which thus expresses itself in precisely the same way as the anodic closure inhibition above described, and cannot be viewed as a mere fatigue effect. If, on the contrary, current *enters* the wall of the heart for a prolonged period by the brush-electrode, a contraction appears immediately after it is broken, in the proximity of its point of exit. This contraction may even be more pronounced than the natural systolic contraction, as appears externally from the paler colouring of the heart-wall. This is the *anodic opening contraction* derived from autonomous descending alteration, the analogue of the *kathodic closure contraction* described above, which depends upon allonomous descending alteration.

"The anodic opening contraction and kathodic opening relaxation are fundamentally analogous with the phenomena of successive contrast, as observed in other living substances, and are as little as these to be referred to a mere fatigue effect."

In contrast with this straightforward exposition, the "modified" molecular theory recently (in 1888) advanced by Bernstein (52) is unsatisfactory, in spite of its elaborate detail. It starts, moreover, with certain postulates that are, at least, doubtful. In the first place, it is held necessary to conceive the living fibres (in muscle and nerve) as consisting of longitudinal series of molecules, looped together at the natural transverse section of the muscle (tendon-end), and "polarisable in the fluid which contains them," although, on account of their close juxtaposition longitudinally, such polarisation can only take place "at the free surface" of the row of molecules. By this hypothesis (which he believes to be confirmed by the inexcitability of the artificial cross-section of a muscle to current), Bernstein explains the inexcitability of the tissues in question to transverse passage of current, since it

is inconceivable that there should be reciprocal neutralisation of anodic and kathodic polarisation, unless the two ions are, so to speak, in immediate juxtaposition. Is it, however, so impossible that the two polarisations should neutralise their respective action upon the living matter, when they merely arise at either border of a visible fibril? Bernstein further supposes that his series of molecules behave in regard to spatial distribution of polarisation exactly like Hermann's core-model, or the equivalent medullated nerve-fibre, and he refers the excitation at closure and opening of the current solely to the appearance of negative and disappearance of positive ions within the collective molecules of the living matter under the electrode—a view that recalls the electrolytic theory of v. Bezold, where electrical excitation is explained by (or at any rate referred to) chemical stimulation from the separated ions.

It is, however, under any circumstances difficult to explain the opening excitation, as also the alterations of excitability that occur during the passage of current, by a purely chemical theory of electrical stimulation, and Bernstein was compelled to lay down further postulates as to the nature and behaviour of the liberated ions. These are:—

(i.) The negative ion at the kathode (oxygen, or an oxygenated element) is the cause of the closing excitation.

(ii.) This ion is constantly reduced by a chemical process, in ratio with the mass in which it is developed.

(iii.) The positive ion at the kathode produces no excitation; it is not therefore reduced, but accumulates.

(iv.) The internal polarisation, more particularly at the anode, neutralises the current in the excitable, polarisable conductor, save for a proportionate remainder—provided the polarisation is not maximal.

The active oxygen separated off from the excitable molecules at the region of the kathode tears apart the labile molecules by its oxidising action, whereupon the intramolecular oxygen also comes into play and induces excitation. The alterations of excitability during polarisation are taken by Bernstein to mean that the molecule charged with negative ions (oxygen) is more easily split up, that charged with positive ions less easily ruptured than the unaltered molecules. More particularly in the kathodic region, throughout the closure of the current, there is a slow but

constant development of oxygen, along with its steady reduction by the oxidisable groups of atoms of the excitable molecules. "With weaker currents this process is not intensive enough to liberate the intramolecular oxygen to any appreciable extent, and thus transmit it as excitation. In principle, however, it is co-significant with excitation, since there is a constant discharge of potential energy. The molecule is thereby thrown into a state of more labile equilibrium, since the freed oxygen slackens its constitution, *i.e.* increases its excitability; the intramolecular oxygen is thereby more readily liberated by any stimulus." With the exception of these special views *in re* the chemical process at the kathode, and its localisation in definitely arranged and preformed "molecules," Hering's theory conforms to that of Bernstein in so far as both assume a constant discharge of energy, or broadly speaking, in other words, a predominance of the dissimilatory process over simultaneous assimilation throughout the kathodic region; *i.e.* both theories fall within the range of the preceding experiments.

Bernstein also has detailed views with regard to the processes at the anode. "The positive ion liberated from the series of molecules has, of course, opposite chemical properties to those of the active oxygen at the kathode." Accordingly, there is no excitation at closure of the current. Bernstein assumes, with regard to the simultaneous depression of excitability, that "the positive ion enters into molecular relations with the excitable molecules of the fibre, and thereby renders the constitution of the molecule more solid." We may thereby conceive "the positive ion as an oxidisable component of the groups of atoms in the molecule, the intramolecular oxygen being in consequence more firmly linked with them as an electro-negative element." Here, again, it is interesting to note the similarity of views between Bernstein and Hering, as to the cause of the discharge of an opening excitation. According to Pflüger's theory as given above, anelectrotonus is a state in which there is accumulation of potential energy corresponding with the increased molecular inhibition. This is interpreted by Bernstein to mean that "not merely is there a firmer combination of the intramolecular oxygen, but that a greater quantity of it can be *assimilated* by the molecule. *Anelectrotonus therefore implies a process of constant assimilation, while the opposite process occurs in katelectrotonus.*"

At break "there is a sudden depolarisation, whereupon the positive ion at the kathode disappears. The firmer combination of intra-molecular oxygen suddenly breaks down, and as the molecule had during the passage of the current collected an over-charge of the same, which it is no longer able to hold, this portion is liberated, and causes a rupture of the molecule, co-significant with excitation." Without going more closely into details of the explanation of opening tetanus, and the modifications of excitability at break, it may be stated that on this theory the inefficacy of transverse passage of current is explained as meaning "that the positive ion locks each excitable molecule in the same degree in which the negative ion slackens it. The liberated negative ion is therefore unable to combine with the oxidisable groups of atoms of the molecule, and remains stationary." This is not the place to enter further into Bernstein's elaborate account of the possible constitution of his hypothetical molecules. He supposes them to consist of N-containing nuclei, longitudinally linked with atoms of Ȯ, while the free superficies is set with oxidisable groups of atoms that are rich in C and free of N. These last react towards the nucleus as electro-positive charges, while the "assimilated" combining O appears at the artificial cross-section as the electro-negative charge of the nucleus (cf. Fig. 111). The ions of molecules are not therefore polarisable in the previous sense, "but are already, in their normal state, charged with certain ions, as though polarised by a foreign current." We have elsewhere shown that Bernstein tries to explain all galvanic manifestations in nerve and muscle by this "*electro-chemical molecular theory*." Yet it may be doubted whether these profound speculations as to the structure of the molecules, and the constitution of living matter, are a better foundation for a comprehensive theory of the correlative manifestations than the straightforward propositions which Hering derives solely from facts, and from the fundamental laws of metabolism. And as Bernstein remarked of du Bois-Reymond's molecular theory, that it gave no further outlook on the mechanical and electrical sides, unless a very one-sided view of the constitution of living matter were adopted, so many will not fail to say the same of his own "electro-chemical molecular theory."

In conclusion, a word must be said as to the prevailing theories of the nature of *conductivity of excitation*, in which, as

Hermann showed, the electromotive action of the conducting tissues is perhaps of the first importance. In view of the fact that muscle as well as nerve can be excited by its own demarcation current, as well as by the current of action of a second preparation, provided the conditions of short-circuiting are otherwise favourable, it is *prima facie* not improbable that the internal short-circuiting of the action current may be an essential factor in the wave of negative excitation (or contraction) also.

If with Hermann (*Handb. d. Physiol.* i. 1, p. 256, and ii. 1, p. 194) we consider the galvanic action of any excited point with reference to its environment, this is found (as shown by Fig. 221, *E*) to consist in the "initiation of minor currents in its immediate vicinity," which are short-circuited within the indifferently conducting sheath of the electromotive tract. As in the immediate proximity of an artificial cross-section, numerous lines of current find exit on both sides of the excited segment at the non-excited surface, and eventually effect an excitation there, while at the excited point itself there is, on account of the ingoing lines of current, a tendency to alteration in the opposite sense. Hermann makes express reference to the presumably high intensity of these minute currents, in which the short-circuiting lines are microscopic, so that the resistance is practically negligible. It is evident that a progressive wave of excitation may well be produced in this way.

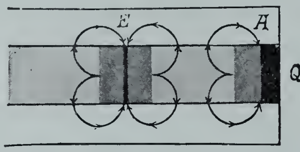


FIG. 221.—Schema of currents in the vicinity of an exciting and a dying point of fibre. (Hermann.)

The Action of Nerve upon Muscle

opens out a further question, which has as yet found no solution.

Notwithstanding the fact that muscle possesses the same independent excitability as nerve, and as living protoplasm in general, the excitation of striated and smooth muscle occurs, in the majority of cases, indirectly from the nerve. The actual process of transmission is thus unknown to us, seeing that muscle cannot forthwith be regarded as a prolongation of the nerve, surrounded with contractile substance, although this view has been advanced on several sides. Here, as elsewhere, it is seen how the physiological conception of a process may, according to

circumstances, be affected by the prevailing knowledge of the morphology of the substrate. Appreciation of the intimate relation between structure and function of an element has not always been as apt as could be desired, and as is indispensable to the fruitful development of knowledge. The strong physical bias obtaining in many minds has obscured the perception that it profits little to substitute general theory and hypothesis for the certain facts of histological investigation. Now, indeed, it is universally accepted that histology and physiology are not two independent departments of science, but are, on the contrary, intimately correlated, each inspiring and attracting the other. Physiology is as much concerned with histological data as with those deriving from physics and chemistry. It is almost superfluous to refer to the recent developments of the cell theory, or to the importance attaching to microscopic methods in general muscle and nerve physiology, and in the theory of secretion. The fundamental significance of an anatomical knowledge of structure to the right interpretation of function has always been recognised for the motor nerve-endings, and for the electrical organs to be described below.

Doyère, in 1840, was the first to observe on a microscopic arthropod, the much-discussed *Milnesium tardigradum*, that the five filaments of nerve entered the muscle-fibres, and apparently terminated in a conical swelling. The motor nerve-endings in striated, skeletal vertebrate muscle subsequently attracted most attention, on the one hand from purely technical reasons, because it was easier to follow the more coarsely-grained medullated fibres to their extreme termination, on the other from the possibility of here approaching the question from its physiological aspect. Frog-muscle, with its nerves, has thus been the prominent if not the sole object of all experiments in nerve and muscle physiology. Without entering into the history of the question, we need only remark that at the present time, thanks to innumerable researches, more particularly those of Kühne (53), it must be regarded as certain that every striated muscle of a vertebrate possesses one or more *distinct* nerve-endings, the structure of which is essentially similar. When the medullated fibre, usually after frequent bifurcation, penetrates into the muscle-fibre, its sheath of Schwann coalesces with the sarcolemma, the axis-cylinder alone passing through to

reach the contractile substance; the medullary sheath, as a rule, terminates shortly before the definite ending. Stress must be laid upon the much-disputed fact of the passage of the axis-cylinder, since, admitting certain premises as to the nature of the propagation of a stimulus, the sarcolemma would offer no absolute hindrance. The axis-cylinder seldom remains entire, but exhibits a more or less copious arborisation (Kühne's *terminal arborisation*), "hypolemmal" in situation, and occurring according to two types, (*a*) in amphibia (Fig. 222), (*b*) in reptiles, birds, and mammals. The former presents tolerably straight, rounded, or flattened terminal branches, running parallel with the axis of the muscular fibre; these extend widely for some little distance close under

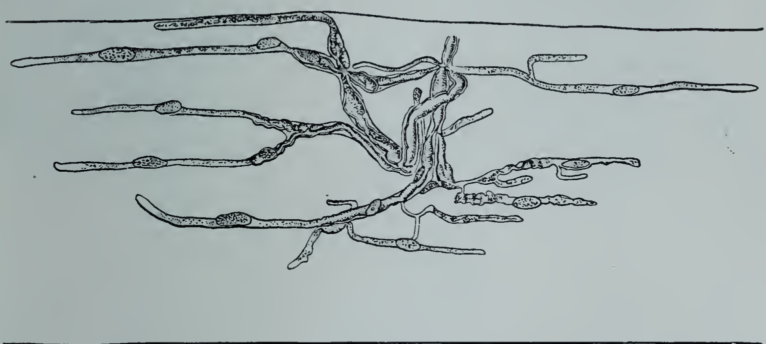
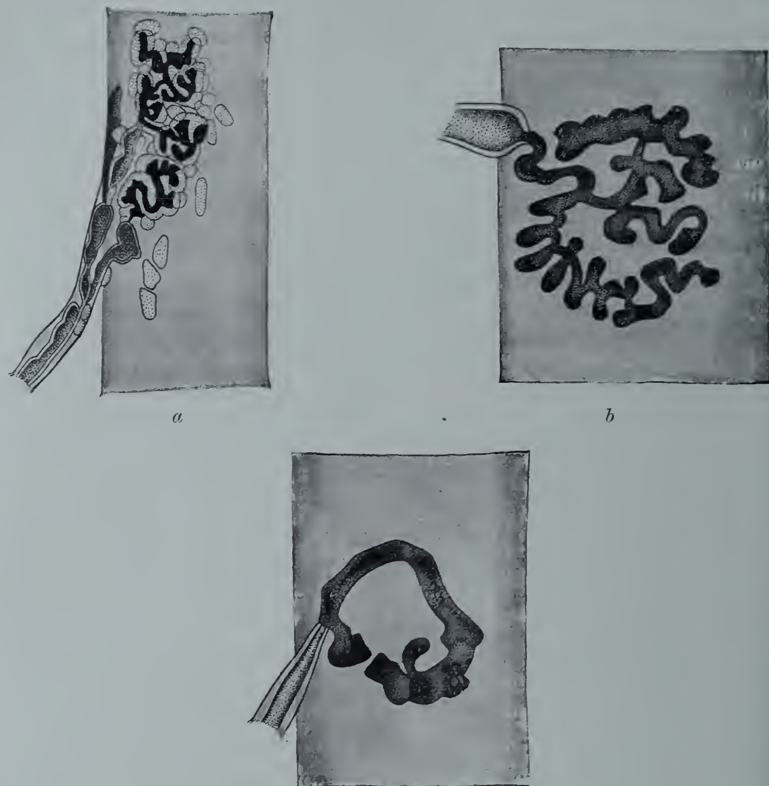


FIG. 222.—Arborisation from frog's gastrocnemius. (Kühne.)

the sarcolemma, and always end distinctly in a blunt point. Here and there they bear long, oval nuclei, which Kühne termed "end-buds." In contrast with these "branches" are the "plates" of other vertebrates, where the rami take a bending and intricate course, or form laminal, lobed expansions within a small circular or oval "field of innervation," that rarely comprises the whole muscle-fibre (Figs. 223-225). It is characteristic of these "end-plates" that they nearly always present a more or less conspicuous accumulation of finely-granulated substance set with nuclei (sarcoplasm), within which are embedded the ramifications of the axis-cylinder (Kühne's "*end-plate*," Fig. 224). In the branched form this "granulosa" is seldom perceptible, while in the plates it is frequently well-developed and appears in profile as a projecting expansion, corresponding with Doyère's expansion in insect-muscle (Fig. 225).

The motor nerve-endings in fishes differ in several respects. Along with such as correspond completely with the "end-plates" of the higher vertebrates (*Myxine, Raja* ; cf. Retzius, 53), there are in the same species a proportion of much simpler forms, in which the axis-cylinder is little if at all bifurcated, after losing the



a *b* *c*

FIG. 223.—End-plates from muscle-fibre of rabbit (*a*), guinea-pig (*c*), rat (*b*). Gold preparations. (Kühne.)

medullary sheath, and lies simply along the muscle-fibre, where it is visible as a very large number of knotty varicosities ("end-discs" of Retzius). Certain amphibians and the higher vertebrates also present innumerable transitions from the simplest forms of ending to the most complicated "branches" and "plates." It is remarkable that a particular type of nerve-ending is sometimes confined to one muscle, or group of muscles, in the same animal.

In the eye-muscles of the frog, the predominating nerve-endings recall the simpler types of low amphibians (*Proteus*) and fishes (Retzius, *l.c.*). The contrast between eye-muscles and skeletal muscles in mammals is in this respect even more striking (cf.

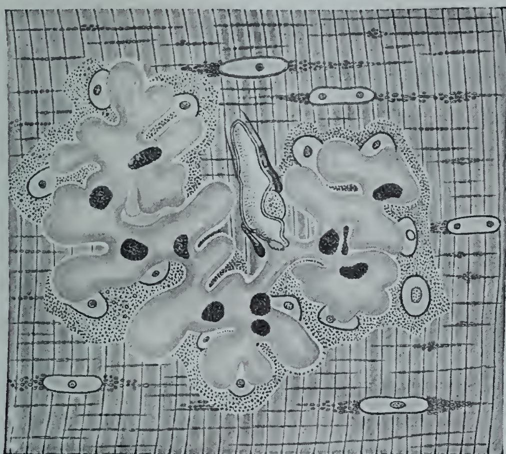


FIG. 224.—End-plates (fresh) of *Lacerta agilis*—in 0·6 % NaCl. Expansion with nuclei.

Retzius, *l.c.* p. 48). While the former invariably exhibit characteristic end-plates, the latter present terminal arborisations which vary in a marked degree from the ordinary type, and again re-

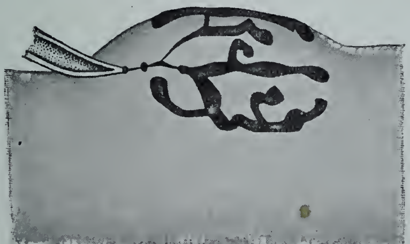


FIG. 225.—End-plates from muscle-fibre of mouse. Expansion of the nerve in profile.

semble the forms that obtain in the lower animals. The rami that extend longitudinally in the muscle are but little branched, and bear a varying number of "terminal discs." Of interest, too, are the "simplest forms of end-branches" observed by Retzius (*l.c.* p. 48) in the same object (and confirmed by Biedermann), which consist of an unbranched non-medullated lateral fork of a

medullated nerve-fibre, "bearing only a single end-disc." In other cases the twig runs on without branching, and bears two, three, or more end-discs, which may be of a considerable size. Every possible transition exists between these simple forms and the most complicated ramifications of the axis-cylinder. But whatever the mode of ending of the motor nerve-fibres, there is never with either gold method or methylene blue an "intravaginal nervous reticulum" in Gerlach's sense (53); the contact between nerve- and muscle-substance is always distinct and confined to the immediate vicinity of the point of entrance. It is obvious that this point is of crucial importance to physiological theory, for our views of the relations between nerve and muscle would have to be considerably modified if it were true, as Gerlach says, "that the presence of nervous elements is implied wherever there is contractile substance, and that no sharp separation between nervous and muscular tissue can be accepted." Long before any good results had been obtained with vertebrate muscle (where, owing to erroneous interpretation of gold preparations, Gerlach's conceptions had been accepted), valuable work was done by means of methylene blue, with the muscles of certain arthropods.

In the crayfish it is easy to stain the nerves of the trunk- and tail-muscles so clearly that no doubt can exist as to the finest endings of the rami of the axis-cylinder. Under such conditions, both the wide band-shaped muscles which run along the ventral surface of the thorax, and the superficial layers of the muscles of the tail, exhibit an extraordinary wealth of nerves. The smallest particle from the surface of a nerve thus stained is seen under the microscope to be interwoven, and studded with a more or less dense tissue of the finest axis-cylinders, stained blue, and characterised by richly varicose swellings. These arise from the branching of the larger trunks (containing several axis-cylinders of unequal size, and depth of stain), which traverse the muscle throughout its volume. Ehrlich, who was first to observe the effect, is of opinion that this really is an "intramuscular plexus" (corresponding with Gerlach's "intravaginal nervous reticulum"), and that there is a fundamental distinction between the mode of nerve-ending in these muscles and in those of the extremities, where (in his words) "the nerves run an isolated course and form superficial ramifications, which rarely stain with methylene blue."

It is undeniable that these marked differences exist. Unless we assume (and in Biedermann's opinion there is no ground for doing so) that the methylene-blue staining of the nerves in the claw-muscles of the crayfish is in all cases very imperfect, the most superficial comparison of two preparations of trunk- and claw-muscles from the same animals, and similarly treated, is sufficient to show the striking difference in the number of nerve end-branches. This expresses itself, on the one hand, in that the terminal rami traverse the whole interior of a muscle-bundle, consisting of numerous larger and smaller groups of striated fibrils, separated by sarcoglia, on the other by a far more copious branching of the several axis-cylinders. In contradistinction from these, the motor endings in the muscles of the claw (as of the extremities) resemble those which are found in the lowest vertebrates. In many respects the mode of arborisation and termination of the nerves in the adductor muscle of the crayfish-claw is of especial interest. It was stated above that the axis-cylinders, of which there are always two of different size within the common sheath of connective tissue, divide dichotomously and very freely, in such a way that *both* axis-cylinders invariably branch at the same point, at each new bifurcation of the nerve-trunk, down to the final endings (cf. Fig. 150). In the coarser branches the small fibres are generally stained as a darker blue, while in the finest terminal rami there is no apparent difference. These contain, within a very thin sheath, two fine fibres of equal diameter, and mostly highly varicose, which cross the direction of the muscle-fibres, and at different points give off the true terminal branches. These are also paired, and seem to end freely within the sarcoplasmic mantle of the muscle-fibre. In rare cases these terminal twigs also exhibit a scanty bifurcation. But there is never here, or in the muscles of the extremities, any such rich plexus of nerves as in the trunk-muscles. A similar type of muscular nerve-endings is met with in insects also, the thorax-muscles of the larger species of locust in particular giving with the same method clear and elegant figures, which, in their abundance of nervous ramifications, frequently recall the trunk-muscles of crustacea. But wherever there are well-marked Doyère's expansions, the bifurcation of the ingoing axis-cylinders is markedly localised, as in the end-plates of vertebrates. Thus in *Hydrophilus* Biedermann found at most two knotty terminal branches

of the axis-cylinder, running in opposite directions, within the substance of the expansion. These are for a short distance parallel with the long axis of the muscle-fibre, and then appear to end freely. In other cases they send out a few short side-branches, the presence of which is sometimes indicated only by isolated dark-blue droplets. Finally, the nerve-endings (in consequence of the great instability of the intrinsically delicate, naked axis-cylinder) often appear merely as an accumulation of greater and smaller, and no longer coherent, drops (stained blue) within the expansion — their real nature being apparent only on comparison with other parts of the same preparation. Similar observations have recently been communicated by Rina Monti (53) upon different insects.

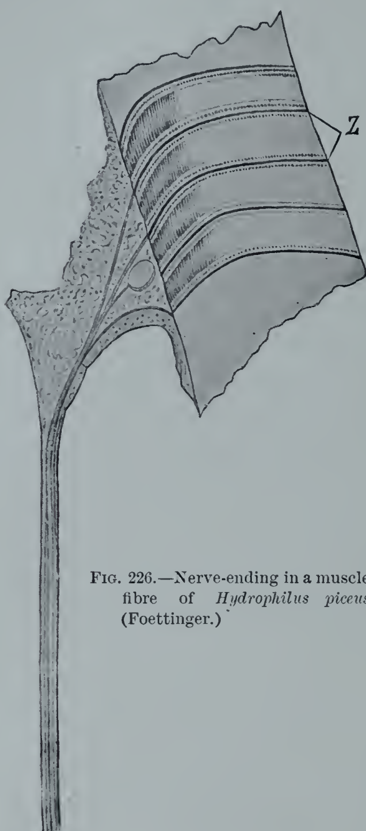


Fig. 226.—Nerve-ending in a muscle-fibre of *Hydrophilus piceus*. (Foettinger.)

Foettinger (53) gives a different account of the motor nerve-endings in insects, pointing to a fundamental difference between vertebrates and insects. In the beetles investigated by him (*Chrysomela cœrulea, Lina tremula, Hydrophilus piceus, Passalus glaberrimus*) there were, as a rule, several, often many, nerve-endings to one primitive fibre, and these—as may be verified on hardened preparations—are frequently (? always) the starting-point of waves of contraction. After treatment with osmic acid and alcohol, delicate fibrils or filaments may sometimes be distinguished in the side-view of a Doyère's expansion; these start from the junction of the ingoing nerve-fibres, and pass to the intermediate discs (Fig. 226). If this be a real irradiation of the axis-cylinder, there must be direct continuity between

certain layers of the striated muscle-fibres and the nerve: thus verifying a conjecture long since hazarded by Engelmann (54), when he defined the isotropous ground-substance of the muscle as "a somewhat modified continuation of the axis-cylinder of the motor nerve-fibres," and distinguished it as "nervous" from the "contractile" tissue. Biedermann's own (methylene-blue) experiments are little favourable to the assumption of any such intimate relation between the final endings of the ingoing axis-cylinder and the intermediate discs, although he has recently devoted special attention to this point. The most favourable preparations of crustacea (crayfish), and of several kinds of locusts (*Locusta* and *Acridium*), failed to show any such relation. Farther investigation of the point is indispensable.

Comparison at once suggests itself between the marked difference in the motor nerve-endings of different animals (and in different muscles of the same species), and the differences of function in the same muscles—such, *e.g.*, as the sluggishness of the claw- and agility of the tail-muscles in crayfish. The experimental data in this direction do not, however, justify any conclusion. Nor must it be taken for granted that the characteristic morphological differences seen in the parallel axis-cylinders down to their final ending (*e.g.* in the abductor muscle of the crayfish-claw) actually correspond with the double innervation here exhibited from the motor and inhibitory nerves, although such a conjecture is by no means unfounded.

Information as to the motor nerve-endings in uninuclear striated and smooth muscle cells of vertebrates and invertebrates is still very imperfect. *The absence of characteristic end-plates in cardiac muscle*, even in the higher vertebrates, is however established, the character and ending of the finest non-medullated rami being usually such that they branch many times dichotomously, and then wind round the muscle-bundles, after which they penetrate into these last, and terminate at the individual cells in very fine, varicose end-branches (Retzius). The same mode of ending seems to prevail in smooth muscular parts, where again there is remarkable similarity with certain very simple forms of nerve-ending in the striated muscles of low vertebrates and invertebrates.

Du Bois-Reymond affirmed that the major part in the doctrine of muscular innervation devolved upon histology, and if

this be true, it is essential to review the known facts of the morphology of motor nerve-endings in vertebrates and invertebrates in order rightly to appreciate the several theories. With this object we have briefly summarised all the relevant data. Starting with the striking anatomical resemblance (which can be histogenetically accounted for) between the motor "end-plates" of striated skeletal muscle in the higher vertebrates and the nerve-endings in the "electrical plates" of the electric organ of *Torpedo* (to be described below), W. Krause (55), followed shortly after by Kühne (56), was the first to express the opinion that the action of nerve upon muscle might depend upon the passing of an electric shock into the latter by means of the end-plates, thereby producing a contraction. From this point of view it must be assumed that the excitation conducted by the nerve to the end-plates induces a brief electrical P.D., as in the electric plates. "One surface of the nerve end-plates, no matter which, becomes positive, the other negative. The resulting electrical shock excites the contractile substance on which it impinges at sufficient density," and a twitch immediately ensues. "Tetanus arises from a more or less compressed series of such shocks." This hypothesis (the so-called "theory of discharge"—*Entladungshypothese*—of du Bois-Reymond) gained acceptance, leading *inter alia* to the conjecture that the secondary twitch from muscle to nerve, discovered by Matteucci, is due less to the production of electricity on the part of the former than to discharges of the intramuscular nerves, or end-plates. Becquerel, without knowledge of the histological relations, had in fact placed Matteucci's secondary contraction in direct parallel with the physiological shock of the torpedo, referring it to an electric discharge in the muscle (cf. du Bois-Reymond, 23, p. 15). Kühne's recent investigations have, however, invalidated the suggestion that there may be discharges from the end-plates. For neither does the region by which the nerve enters, which is especially rich in end-organs, exhibit any greater secondary activity than other poorly-innervated or nerve-free tracts of muscle; nor did Kühne, in carrying out a method of du Bois-Reymond, succeed in obtaining secondary twitch from muscles in which excitability had been abolished, with careful preservation of the intramuscular nerves (Kühne, 2, p. 42). This does not, however, contradict the "theory of discharge," which refers primarily to the relation

between motor end-plates and corresponding muscle-fibres, and we must therefore cite it in detail. Du Bois-Reymond gives the whole argument in his well-known treatise, *Experimental Critique of the Theory of Discharge* (57). If each end-plate is

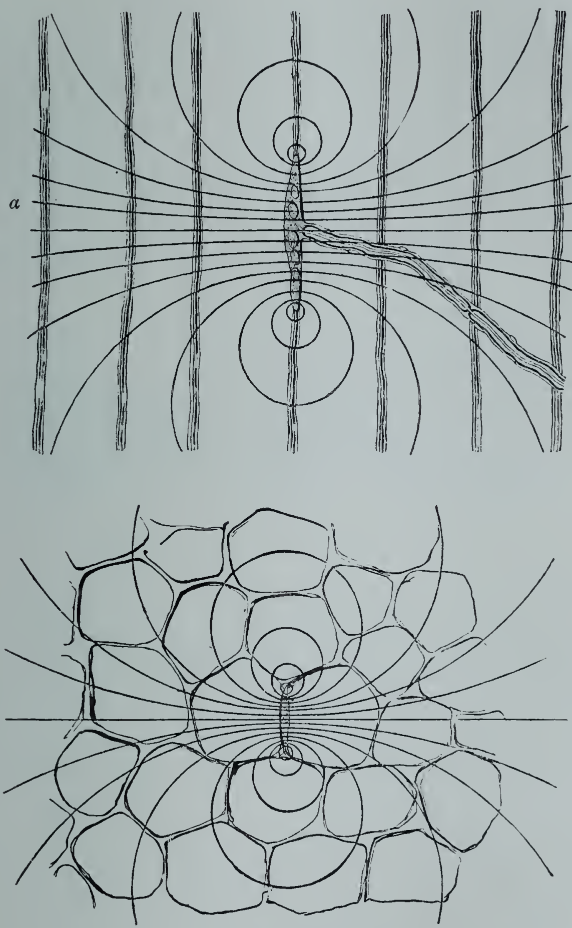


Fig. 227.

conceived as developing opposite potentials when excited at the dorsal- and under-surfaces, like an electrical plate, then—the two surfaces of the plate being presumably isoelectric—the resulting lines of current will be according to du Bois-Reymond's schema (Fig. 227, *a*, *b*).

It is evident that not merely the muscle-fibres corresponding with the plate, but those surrounding it also, would be similarly excited; under normal conditions, however, this is experimentally found not to be the case. Moreover, the lines of current traverse the adjacent fibres at right angles to the long axis, *i.e.* in the ineffective direction. There are certain artificial, and therefore *a priori* improbable, conditions under which such a distribution of potential might come about in the plate, "that the resulting current through the corresponding fibres should be perceptibly denser than in the adjacent fibres," but these commend themselves the less in that they at once destroy analogy with the electrical plate. It is, *e.g.*, conceivable that a P.D. should arise at the under-surface only of the end-plate, on excitation (Fig. 228); this would then

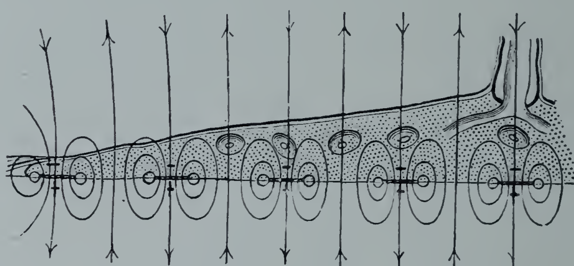


FIG. 228.

at the moment of discharge form "a mosaic of positive and negative points, between which only molecular currents circle, and these, at a distance equal to the least diameter of the plate, would be of imperceptible density." Considering further that the facts of comparative histology of the motor nerve-endings are in direct contradiction with the theory of discharge, since the presence of true typical end-plates appears to be confined to the muscles of the higher vertebrates, a few fishes, and insects, the theory in its original form is hardly tenable. Du Bois-Reymond accordingly proposed a "*modified* theory of discharge"; but this is scarcely more acceptable than the first, since its postulates are equally inadequate.

"Definite anatomical relations are required to account for the inefficacy of the process towards adjacent muscle-fibres, and should consist in a slight, hook-shaped curvature of the extreme end of each hypolemmal nerve-fibre on to the surface of the con-

tractile cylinder, its direction being towards the axis of the rami" (du Bois-Reymond, *l.c.* p. 555). To the end-surface of each hypolemmal nerve-hook, du Bois-Reymond ascribes the properties of an artificial cross-section, pre-eminently that of negative potential in relation to the "natural long section" of the terminal fibre (Fig. 229). The negative variation of this pre-existing current is the stimulus for the muscle-substance with which it is in contact, and this implies the further, and highly improbable, supposition that the muscle-substance is sensitive to such a weak stimulus as the negative variation of the nerve current. Kühne (11, p. 90 ff.) instituted many experiments, as varied as possible, with the view of discovering practical evidence for the modified theory of discharge, or any parallel hypothesis, but with no

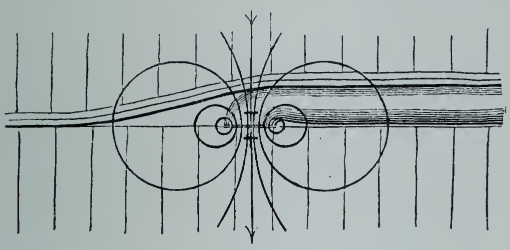
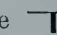


FIG. 229.

result. What du Bois-Reymond claims for a single primitive fibre was not to be elicited on applying a vigorous frog's nerve, containing many hundred fibres, to a muscle under the most favourable conditions, and then exciting it; nor did the artificial transmission of excitation from nerve to muscle come off any better with the non-medullated olfactorius of pike, in which the E.M.F. is much higher (Kühne's method).

Kühne himself, on the strength of his comprehensive researches into the morphology of motor nerve-endings of vertebrates, attempted subsequently to refer the innervation of the muscle to electrical processes within the excited nerve; but this hypothesis went the way of all its predecessors, when confronted with the growing knowledge of the motor nerve-endings in invertebrates. Kühne tried, by comparison of innumerable single cases, to reduce the two main types of hypolemmal nerve-endings in vertebrates, *i.e. plates* (reptiles, birds, mammals, fishes), and *terminal fibres* (arborisation of amphibia), to the simplest possible

schema, in order "to arrive at what was common to all, or to the last reduction that still preserves the type of the ending."

In *Salamandra*, where the motor nerve-endings consist entirely of non-medullated, non-nucleated terminal fibres, embedded directly, with no intermediate element, between the sarcolemma and the contractile tissue, the simplest form = , where the stronger stem represents the last epilemmal, medullated nerve, the lines at right angles being the intramuscular end-fibres, approximately parallel with the fibres of the muscle. Asymmetrical forms = , , frequently appear, never the simple  form. As against these, the "plates" of the higher vertebrates are chiefly characterised by the bulging walls of the branches, studded with small lobes, or humps. Here too, however, a closer inspection detects the asymmetrical branching of the end-rami (characteristic of arborisation), "with sharp angles like a bayonet" ("never in the form of a tuning-fork"). "This discloses another feature, to be interpreted in the same sense, *i.e.* the arched and recurrent curvature of the branches, their lateral or terminal prominences lying so close together that they only embrace very small bridges of muscle." "This arrangement presents every transition, from the simplest, consisting of a single loop, curved on the surface and humped, to the more circumscribed and labyrinthine plates, which form expansions with circular, elliptical, and oblong bases. The simplest schema therefore = , the more complex ." To this character of the terminal fibres Kühne refers a peculiarity in the excitatory waves impinging on them, "which is of some importance to muscular excitation," since "in the never-failing homodromous fibres no waves can advance in a parallel course without exhibiting phasic differences." "In view of Bernstein's remarkably steep, almost vertical decline of the wave of electrical variation in nerve, the distances between the terminal fibres running parallel with each other and the nearest root must be sufficient to initiate a considerable P.D. between each pair of points connected by a perpendicular." "Between these points, which have diametrically opposite signs, if the wave of variation is, in Bernstein's sense, heterodromous to the nerve current, there is, however, muscle-substance, which must complete the circuit of the potential." Kühne thus imagines that a current completes itself between opposite points of the terminal branches of ingoing

nerves, in consequence of the phasic differences in the wave of excitation, which current excites the intermediate muscle-substance. This, hypothesis, too is open to objection, not merely from the theoretical point of view (du Bois-Reymond, 58, and Bernstein, 59), but still more (*supra*) on anatomical grounds, more particularly the character of the motor nerve-endings in all invertebrates.

To sum up all that has been said in relation to these various "discharge theories," their justification seems more than doubtful, and we must rather subscribe to Bernstein's opinion (*l.c.* p. 337), that every hypothesis whereby the muscle is to be excited by an electrical shock irradiating outwards from the nerve-ending is excessively improbable. Apart from the preceding objections, the time-relations of muscular excitation are decidedly against such a view. The point is whether a measurable time is required for the propagation of the excitatory process from the nerve-ending to the muscle. Yeo and Cash pointed out that the latent period, with indirect stimulation of the gastrocnemius muscle, is considerably greater in the immediate vicinity of the entrance of the nerve than it is with direct excitation of the muscle, and Bernstein (59) subsequently examined the same fact more closely.

"The marked extension of the time-difference (0·0032–0·0049 sec. on an average) leads us to infer that it depends not merely on transmission of the excitation in the nerve down to its entrance into the muscle-fibres, but also upon the retardation of the excitatory process in the end-organ of the nerve-fibre, as compared with its duration in any parallel tract of the same." Subtraction of the period of conductivity in the nerve from the interval determined experimentally between the two curves of contraction gives the presumptive "*period of excitation in the nerve-ending.*" If, in view of the structure of the gastrocnemius muscle, we take the central point of the whole muscle as the central point of entrance for the nerve, estimating the rate of nervous conductivity at 27 m. per sec., then, according to Bernstein, the period of excitation of the motor end-organs will on an average be $0·0032 = \frac{1}{312}$ sec. The same value appears, as Bernstein pointed out, from the latent period of the negative variation with indirect excitation of the muscle. We must assume that the negative variation begins at the point of excitation at the moment of stimulation (*i.e.* with no perceptible latent period), in natural excitation from the nerve-ending, as in artificial electrical

stimulation of the muscle. Then, on subtracting the period of nervous conductivity from the latent period of the negative variation, as observed with indirect excitation of the muscle, the remainder will again be the excitation period of the nerve end-organ. Certain observations of Tigerstedt may be interpreted in the same sense, showing that in direct excitation of non-curarised muscle, maximal twitches may sometimes appear with sub-maximal strength of stimulus, in which the latent period is to a marked degree more extended than it would be in maximal stimulation. Again, twitches of medium and minimal height are distinguished in non-curarised muscles by a longer latency than the corresponding twitches of curarised muscles.

Hoisholt (60) subsequently disputed the justice of Bernstein's conclusions, on the strength of experiments performed under Kühne's direction. He equally observed (on sartorius and gracilis) a much shorter latent period on stimulating the richly innervated muscle-substance near the hilus, than with excitation of the ingoing nerve-trunk at the same point; but found, on the other hand, with direct stimulation of the non-innervated terminal sections of the muscle, that there was not merely an equal but even a far more prolonged latent period than with indirect excitation of the nerve. Hoisholt believed himself able to explain these facts by summation of stimuli in the muscle and intramuscular nerves; against which Boruttau (60), on the strength of his experiments, urged the validity of the first view, confirming with supramaximal excitation the difference, as found by Bernstein, for parallel-fibred muscle also, on stimulating it first indirectly, and then from the nerve-free end. The latent period was invariably shorter in the latter case. L. Asher (60) objected to this, that a supramaximal stimulus cannot be sufficiently localised to the non-innervated end of the muscle. At Kühne's instigation, Asher employed a new method in which parts of the muscle, free from, and containing, nerves, should twitch *separately*, and describe a curve under absolutely parallel conditions. In the successful experiments, which were not numerous owing to the shortness of the bits of muscle employed (these being hung parallel with, and close to, one another), and consequent difficulties of experimenting, the two curves fully correspond at the initial point, and exhibit the same latent period. In spite of this, the protracted latency on stimulating the nerve-trunk demands farther

investigation. Should this eventually establish the conclusions of Bernstein's hypothesis, a "theory of discharge" would still be possible only under the assumption "that, after the wave of excitation had reached the end-organ, the electrical charge would at first develop slowly, and only after about $\frac{1}{300}$ sec. reach the climax at which excitation of the muscle would be effected."

Since it has been established by Kühne that the final expansion of the axis-cylinder is *hypolemmal* in striated muscle-fibres invested with a sarcolemma, a theory of discharge, in the original sense, no longer seems to be necessary to the explanation of innervation. On the other hand, we cannot overlook the possibility that there may be *direct* transference of the molecular processes fundamental to excitation, from nerve to muscle; just as, in both tissues, transmission of excitation occurs from section to section. This in no way excludes essential participation of Hermann's galvanic processes (as set forth above), but, on the contrary, renders it highly probable. No real objection exists in the fact that, since actual continuity of substance between nerve and muscle has not thus far been proven, the conductivity of excitation must occur *per contiguitatem*. Recent evidence, moreover, tends to show that transmission of excitation may occur by contiguity alone in the central nerve-endings also.

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CHAPTER XI

ELECTRICAL FISHES

I. Structure and Constitution of Electrical Organs

The wonderful physiological properties of certain fishes, *e.g.* more particularly the *Torpedinidæ* of the Mediterranean, and the Siluroids (*Malapterurus electricus*) of the Nile and other African rivers, have been known and dreaded from the earliest times. The most superficial acquaintance with any representative of this small and highly specialised group of fishes at once reveals their power, when touched, of exhibiting activities, which were first shown to be similar to electrical discharges by Adanson (1751). Francesco Redi (1666) had long since pointed out, in his masterly anatomical investigation of the electric ray (*Torpedo*), that the mysterious power of the electrical fishes was, in all likelihood, associated with special organs, situated symmetrically on both sides of the head. These he described from their shape as "sickle-shaped bodies, or perhaps muscles." "It appeared to me," writes Redi, in describing his experiments, "as if the painful action of the electric ray was located in these two sickle-shaped bodies, or muscles, more than in any other part." From this may be dated the first scientific treatment of the problem. For centuries it had sufficed to describe the striking and unpleasant sensations resulting from unwary contact with electrical fishes. The Latin name *torpedo*, the French *torpille*, the Italian *tremola*, the old Greek *narke* for the ray, the Arabic *raâd* or *raâsch* for the cat-fish, and the Spanish *templador* for the South American eel, all point to the stunning and shattering effect of the shock from an electric fish, without hazarding anything as to the cause of the manifestation.

Redi's predictive designation of the electrical organs of *Torpedo* as "muscles" led, in the first instance, to a purely mechanical theory of their action, which was most clearly set forth by Borelli (1685). He assumed that the organs contracted rapidly several times in succession, thus giving to the limbs in contact with them a series of vigorous shocks, which produced a cramp similar to that due to a blow on the elbow. This theory was universally accepted,—the most famous scientists, Réaumur, Linnæus, Haller, sanctioned it,—and it may be said by 1750 to have reigned supreme as the sole possible, and at the same time adequate, explanation. Soon after the discovery of the Leyden jar (1745), a French botanist, Michael Adanson (1751), travelling on the Senegal, became acquainted with the far more energetic action of *Malapterurus*, the shocks from which at once impressed him (as previously noted by Gravesande; du Bois-Reymond, 4 *e*, p. 127) by their similarity to discharges from a Leyden jar, more especially as it was found possible to lead them off by long wires. The same was reported by Dutch explorers from Surinam, of *Gymnotus*, the first account of which reached Europe in 1672. It was found that the shock would pass through a circuit of several persons, and, like the electric current, could only be conveyed by conductors, and not by insulators (Williamson, 1773). Walsh had discovered the same in the previous year at La Rochelle for *Torpedo*, and thus for the first time established the electrical nature of the discharge (du Bois-Reymond, 4 *c*, p. 418). He showed at the same time that the back and belly of the fish give a different electrical reaction at the moment of the shock, and therefore held the "sickle-shaped muscles" of Redi to be an electrical apparatus, which the animal could throw into voluntary activity. In a gymnotus sent in 1775 from Guiana to London, Walsh saw sparks leaping over a gap in the discharging circuit, and was able to show the experiment ten or twelve times consecutively to the Fellows of the Royal Society (3, p. 158). From this time the attention of explorers in this department was mainly directed to establishing the complete identity of the discharge from the fish with the electrical current. Cavendish (1776)—whose investigations on *Torpedo* were so extensive that (as du Bois-Reymond pointed out) Faraday was the first to recover the same standpoint—attempted to imitate the action of the shock by ordinary electricity. On a

leather model of the fish, saturated with sea-water, he covered the organs corresponding to the poles with tinfoil, connecting them by insulated wires to a Leyden battery. In this way he made a true picture of the distribution of potential (lines of current) outside the fish in the surrounding water, and then showed how a hand dipping into the water must feel the electric shock without actually coming into contact with the fish, the intensity being greater in proportion as the hand is nearer the fish. This agrees with the observations of van der Lotts (4 *e*, p. 128) in 1762, to the effect that a shock can be given through the air, which the electric eel projects through its air-holes; as well as the later observations of C. Sachs that the jet of water from the bung-hole of a vessel containing a gymnotus may conduct the shock.

The discovery of galvanic electricity, and subsequent dispute between Galvani and Volta, could not fail to be of great importance to the theory of electrical activity in these fishes, as the most pronounced manifestation of animal electricity; while here, as so often elsewhere in physiology, the mechanism of the electrical organs was referred directly to the dominant physical theories. Volta himself detected the analogy between the pile which he discovered, and the organ of the torpedo, which is built up of prismatic columns (*Collezione dell' Opere*, etc., Florence, 1816, t. ii. pt. ii. p. 99); and even defined the pile as an artificial electrical organ. Such a theory, according to which electricity is developed from the contact of three dissimilar elements, had to encounter great difficulties, foremost among which is the *constant* action of the pile; while the activity of the electrical organ is obviously under the control of the animal. These objections were got over by conceiving the fish to execute certain movements in the act of discharging, by which the supposed electromotive elements of its batteries, the nature of which was quite unknown, were first brought into contact (Volta); or by conjecturing the outflow of a defective constituent at the will of the animal (A. von Humboldt). One great difficulty was the impossibility of insulating the organ, which led Valentin (34) at the beginning of the forties to ascribe to the tendinous septa that surround the columns (prisms) of the organs the function of insulators. Schönlein, at the same time, held that the gymnotus could voluntarily insulate itself from the surrounding water.

The uncertainty (notwithstanding the apparent proof of the

electrical character of the discharge) of all these more or less hardy speculations is best seen in the fact that, even in 1829, Humphry Davy (whose brother, John Davy, at his instigation, made extensive researches on *Torpedo* at Malta), expressed doubts as to whether the electricity of the electrical fishes were really identical with ordinary electricity; while Faraday (who had the good fortune to be one of the first who investigated that most powerful of all electrical fishes, the South American eel, with the best physical aids that Europe could supply) was unable a few years later to procure from the discharge of the gymnotus the eight effects which he laid down as essential to the identity of all electricity (viz. sparking, thermic action, attraction and repulsion, deflection of magnetic needle, magnetisation of steel rod, hydrolysis, conduction through hot air, physiological action). At a later period, one blank only remained, failure of conductivity through hot air.

It is to du Bois-Reymond that we owe the fundamentals of a scientific physiology of electrical fishes, founded no less upon theoretical considerations than upon sound experimental investigation. His data have been amplified by later workers, and the main points, at least, may now be taken as established.

Since the more recent contributions to the subject are only intelligible if the structure and finer relations of the organs have been mastered, it is, in the first place, advisable to give some detailed account of these, taking the *Torpedinidæ* as the best known representatives of the group; their structural relations being the simplest and most obvious. Fig. 256 *a* represents half the dorsal aspect of *Torpedo marmorata*, after removing the skin. On either side of the head and branchial sacs lies a kidney-shaped organ, running right through the highly-flattened, broad body, from dorsal to ventral surface. From the superficial aspect these resemble a honeycomb, consisting of irregular 5- to 6-sided prismatic columns in juxtaposition. A section vertical to the plane of the body shows that the columns decrease in height from within outwards. They are separated by partition-walls of connective tissue, and in fresh preparations resemble, both in appearance and in consistency, a grayish-red, semi-transparent jelly.

The finer structure can be examined both in longitudinal sections, parallel with the axis of the columns, and from the super-

ficial aspect. The latter is easily obtained by a method first employed by Savi; this consists in cutting off the convex transverse section of a column with scissors, and then separating out the single thin plates of which it consists, in some indifferent fluid. It is these fine discs, lying one upon the other like the coins in a rouleau, or the plates in a voltaic pile (Fig. 230), which (as du Bois-Reymond was the first to point out) become electromotive under the influence of the nervous system. "The electromotive components of the primitive batteries of the fish's columns must not be sought in optically separable structures, in heterogeneous, contiguous tissues, or in animal fluids. The seat of E.M.F. lies rather in the centre of a morphologically homogeneous tissue, the so-called 'electrical plate'" (du Bois-Reymond 4 *d*, II.).

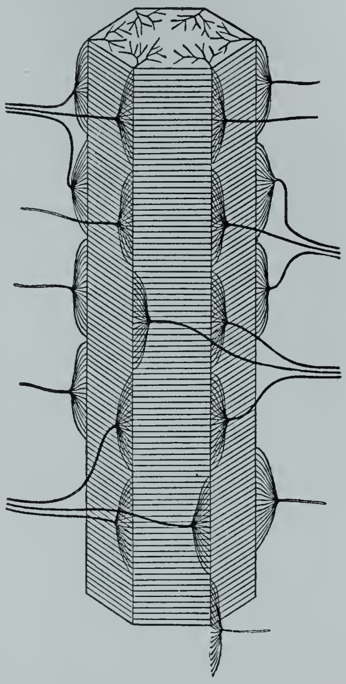


FIG. 230.—Schema of a single prism in *Torpedo* with ingoing nerve (Wagner's *end-brush*). (Fritsch.)

In their normal position *in situ* the plates are approximately horizontal, curving only in the middle towards the back of the animal. On treating them with reagents, however, various strata appear in the longitudinal sections. Each plate seems to be bent backwards at the margin, where it is attached to the connective-tissue septa, the ventral half being more particularly involved (Fig. 231). The single plates are somewhat further apart in the larger than in the smaller columns. From the ventral aspect, each plate exhibits a rich plexus of nerve-fibres, with a sprinkling of capillaries, embedded in a gelatinous tissue studded with star-cells, which fills the intermediate spaces of the plates, and gives the appearance of a quivering jelly to the fresh substance of the prisms. When we remember the number of nerve-fibres in each single plate, the wealth of nerves in the entire organ is surprising, and witnesses to its intimate relations with

the central nervous system. This is no less strongly marked at the origin of the "electrical nerves," which arise from two special lobes of the brain, that are wanting in all other fishes. Lorenzini, 1677 (as was pointed out by Boll, 5 *d*), described these parts as a posterior pair of tubercles, without divining their function, while A. v. Humboldt was the first to recognise them more exactly for the centres of the electrical nerves of *Torpedo*. After exposing the central organ, they are perceived as two long grayish-yellow bodies lying close together, from which four nerve-trunks run out right and left, on either side, and supply the organs. According to Fritsch (whose view was also adopted by Schenk on developmental grounds), the dorsally protruding electrical lobes arise from branches of the motor nuclei of the vagus, in the medulla oblongata, which, from the excessive proliferation of the ganglion-cells that subserve a special function, appear to be pressed upwards from their original seat on the floor of the fourth ventricle. Transverse sections reveal a dense layer of large ganglion-cells, the axis-cylinder processes of which pass directly into the fibres of the electrical nerves.

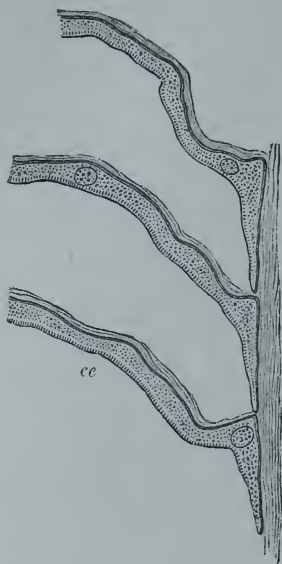


FIG. 231.—Marginal portion of three electrical plates: longitudinal aspect of the column. (Ranvier.)

The character and distribution of the nerves that enter the organ within each single column, or prism, is highly characteristic. As Rudolf Wagner (35) first showed, the fibres all divide up suddenly into many branches before they enter the plates,—forming the characteristic bundle (Wagner's *brush*—Figs. 230 and 232), of which the spatial distribution, and relations to the single plates, were determined more exactly at a later period by A. Ewald and Fritsch (9).

They found that the fibres of a brush, about eighteen in number, are superposed upon one another in regular arrangement, entering by the corners of the hexagonal plates; so that each plate is supplied by six fibres, which again present a rich dichotomous ramification (Fig. 230).

So soon as a medullated twig of Wagner's *end-brush* reaches the plate with which it is correlated, and one part of which

Fig. 232.—Portion of an electrical plate with vessels and nerves, which last originate from the ramification of an end-fibre of Wagner's *brush* (*W*). (R. Wagner.)

it is to innervate, it gives off branches on either side, at an approximately right angle. These are still medullated, and in

their turn divide repeatedly (dichotomously), or give off lateral branches; and finally, after losing the medullary sheath, form two horned bundles of non-medullated, pale fibres, the final ending of which in the substance of the plate can hardly be detected (Fig. 233). Not only the dichotomous branches of the medullated, but in part those of the non-medullated terminal arborisations also, are invested with a sheath of connective tissue with embedded nuclei, which is more particularly developed in the former.

FIG. 233.—Arborisation of nerves on the ventral surface of an electrical plate o *Torpedo*. (Ranvier.)

According to Ranvier, this sheath ends suddenly at a given point of the non-medullated terminal expansion.

Remak, 1856 (27), was the first to observe that the fine non-medullated terminal branches can be followed much farther than is described by Wagner. In good preparations the whole of the apparently empty intermediate spaces proved to be filled with pale and visibly anastomosing nerve-branches. Kölliker, 1857 (16 *b*), and later on M. Schultze, described a true nervous network, which Schultze represents as a very fine reticulum

with nearly quadratic meshes (31 *b*). The majority of later workers have determined by the help of modern methods (in particular with metallic impregnation, *e.g.* gold, silver), as also on fresh electrical plates of *Torpedo*, that the nerve-endings are in all respects homologous with the motor end-plates of striated muscle in the higher vertebrates. If we examine Ranvier's picture of a small portion from the terminal arborisation of the nerves of the plate, treated with silver (Fig. 234)—or such figures as are given by Ciaccio (6), Boll (5), Krause

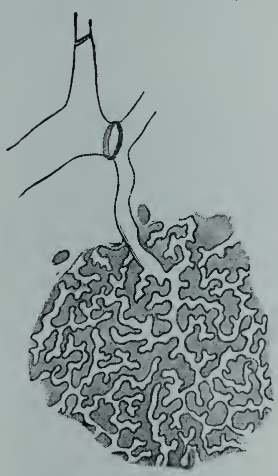


Fig. 234.—Small portion of the terminal nervous arborisation in electrical plate of *Torpedo* (silver preparation). (Ranvier.)

Fig. 235.—Portion of nervous ramification in a plate of *Torpedo*, showing Boll's punctuation. (Ciaccio.)

(17), and recently Ballowitz (2) and Iwanzoff (15), after treatment with osmic acid, gold chloride, hæmatoxylin, Golgi's method, etc.—the exactness of the comparison is at once obvious, and it is difficult to understand how Fritsch (12) could entirely deny the existence of such a terminal nervous arborisation. Biedermann has invariably been able to recognise it in fresh preparations, where it covers the whole ventral surface of each disc like a gigantic end-plate. And, indeed, when we consider the development of the electrical plates from metamorphosed, striated muscle-fibres, the homology between the terminal nervous arborisations on the ventral surface and the motor end-plates can hardly be disputed. Schönlein even states that he is now

inclined to regard the whole of the developed plate as the homologue of the motor end-plate *only*. Remak (*l.c.*) drew attention to a peculiar and regularly arranged punctuation upon the ventral surface of each electrical plate (as observed by all later workers), which Boll (5) described many years later as a new structural relation. This consists of a remarkably fine, regular, and homogeneous punctuation, immediately subjacent to the terminal network, viewed from below (Fig. 235). The arrangement of dots corresponds perfectly with the configuration of the terminal network, so that the little points follow the reticulation of the net, and to some extent mark its distribution. Several (2–3) irregular rows of dots correspond, for the most part, to the single threads of the net, the number of points in 1 sq. mm. amounting, according to Krause and Iwanzoff, to about a million.

In optical cross-sections of the plate (at the bending-points) the punctuation is seen to be the expression of a fine and regular striation, vertical to the surface (cf. Fig. 231, *ce*), which extends from the ventral side to the border of the first sixth of the diameter of the plate (palisade border, Ranvier's *cils electriques*), and was known to Remak, who regarded the dots of the superficial aspect as the bending-points of small cylinders arranged in a palisade upon the surface. Krause in the main subscribed to the same opinion, regarding the dots as "the optical expression of small cylindrical rods, viewed from above, which belong to the neurilemma, and form as it were 'nails,' riveting the flattened terminal fibres." Boll, Ranvier, Ciaccio, and Trinchese viewed them as the true, terminal nerve-endings. According to Iwanzoff the palisade merely represents the processes of the structureless membrane which clothes the lower surface of the electric plates, corresponding with the sarcolemma of the muscle-fibre.

Fritsch, on the contrary, holds the dots (which look black when treated with osmic acid, and examined under the highest dry power, or a weaker immersion lens) to be "the optical expression of strongly refracting and closely approximated granules, embedded in a less refractile, semi-fluid substance, which covers the lower surface of the plate." Fritsch proposes to call this layer, which has nothing to do with the true nerve-ending, the *stratum granulosum*. Its relation to the other layers of the electric plate is most plainly seen in transverse section (Fig. 236).

According to Fritsch (who is again contradicted by Iwanzoff), "it is possible, in specially favourable parts of the cross-sections of a plate, to discover fine threads of nerve at right angles to the direction of the plates, entering at the granular layer and disappearing between the granules." Beyond these again, in the palisade border, they are plainly visible, and form the direct boundary of the palisade (Fig. 236). Their proper ending seems to be at the dorsal border of this layer, in "soft protoplasmic bodies, which in the preparation cohere in spherical (berry-like) masses." Beyond the border of the palisade comes the dorsal ("muscular," Fritsch; "metasarcoblastic," Babuchin) part of the plate (Ranvier's *couche intermédiaire*). This layer, which is

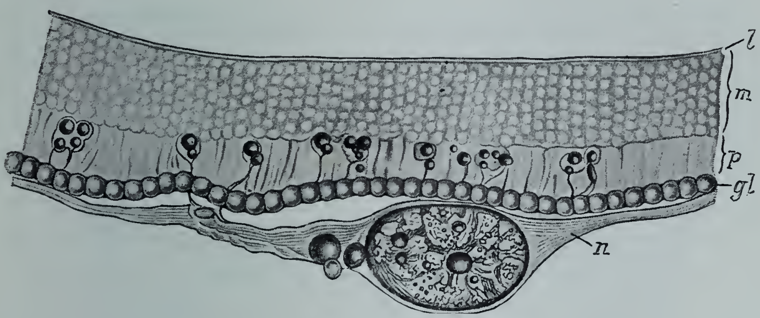


FIG. 236.—*Torpedo ocellata.* T.S. of electrical plate with dependent nerve. l=dorsal border, or layer, of connective tissue; m=*stratum moleculare*; p=palisade-border with nerve-endings; gl=*stratum granulosum*; n=nerve. (G. Fritsch.)

developed by the transformation of embryonic muscle-substance, exhibits nothing further of the characteristic structure of striated fibres. Krause, indeed, describes "striated, bowed fibres" as a residue of muscle-fibrils, but other observers have not detected them. According to Fritsch, this layer, like the *stratum granulosum*, "is composed of minute particles, set in rows parallel with the axis of the prisms, and little more refractile than the intermediate substance" (Fig. 236, *m*).

Fritsch inclines to regard the regular structure (as observed by him) as a confirmation of du Bois-Reymond's molecular theory, though he does not go so far as to affirm that the rows of particles are actually "the required electromotive molecules." Iwanzoff, on the contrary, views them merely as a kind of honeycomb or foam-like structure of the plasma of which the "intermediate layer" consists.

To summarise the main points relating to structure, and more particularly to innervation, of the organ of *Torpedo*, this much is certain. Each ganglion-cell of the electric lobe in the brain gives off an axis-cylinder process (analogous to Deiter's process in the ganglion-cells of the spinal cord), which continues as an unbranched constituent of the electric nerve, down to one of the columns that compose the organ. Here the medullated fibre suddenly breaks up into a number (12–20) of small ramifications (Wagner's *brush*), which are arranged regularly, one over the other, and each partially supply a plate. On entering the mucous tissue that fills up the space between every pair of plates, each

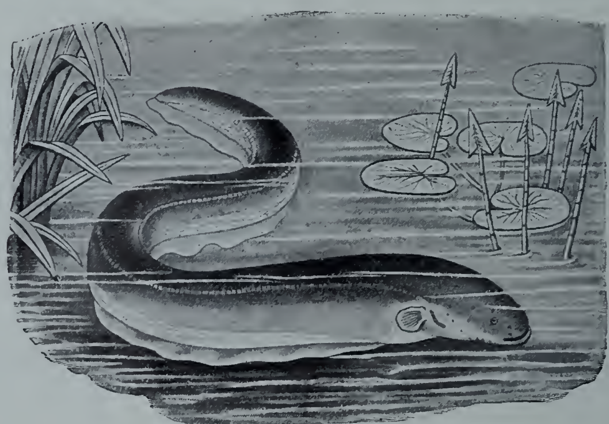


FIG. 237.—*Gymnotus electricus.*

terminal fibre divides many times dichotomously, and finally ends, after losing its medullated sheath, at the ventral surface of the plate, in a manner analogous with the terminal ramification of the axis-cylinder in the motor end-plates of striated muscle-fibres. The nature of the true ending and whether it is free, or, as Fritsch says, lies within the palisade layer, is still undecided, and awaits further investigation.

The uniformity of structure and internal relations in the electrical organ is of great moment to the theory of the discharge of these fishes. In *Gymnotus*, as in *Torpedo*, the organs exhibit a bilateral symmetry, and are so powerfully developed that the fish might be said to consist principally of electric organs. Fig. 237 is a good representation of the form of the fish. Notwith-

standing its eel-like shape, the body-cavity occupies but a small part (not quite one-fifth, including the head) of the total length, while the four electrical organs fill up the space that would otherwise be devoted to the abdomen (C. Sachs). As seen from above, the trunk of the fish appears to taper off behind like the blade of a knife. The gymnotus, in comparison with other electrical fishes, reaches a considerable size (according to Sachs the length may be 155 cm., or 170 cm. according to v. Humboldt), while the species of torpedo most common in Europe measures, at most, 20–30 cm., rarely 70 cm. The electric ray peculiar to the coast of Eastern America (*T. occidentalis*, Storer) is the sole species that becomes double this size under certain conditions, and may be defined as the largest and heaviest, if not the longest, of all the electrical fishes (Fritsch).

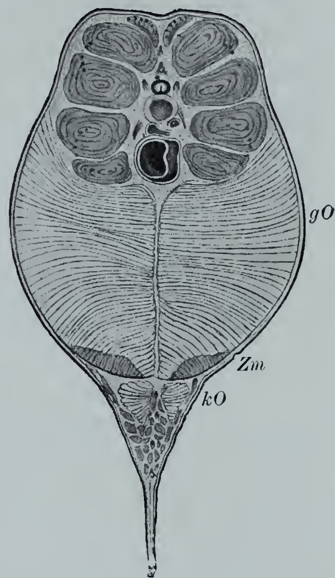


FIG. 238.—T.S. through trunk of *Gymnotus*. *gO* = great organ; *kO* = small organ; *Zm* = intermediate muscular layer.

As seen in a transverse section of *Gymnotus* (Fig. 238), the body consists mainly on the farther side of the head and body-cavity, of a gelatinous, transparent mass, which forms on each side a large, and a second much smaller accumulation, situated below. These are separated by a layer traversed by muscle-fibres, termed by du Bois-Reymond the "intermediate muscular layer," and viewed by Fritsch as a vestige of the muscles whose transformation gave rise to the greater organs (Fig. 238).

Closer inspection proves the substance of the organ to be penetrated by parallel walls of connective tissue, lying one above the other, and running, in transverse section, from a middle, vertical septum to the external circumference of the body. These "longitudinal partition walls," which (as shown by the lateral aspect, Fig. 239) extend throughout the entire length of the organ, including the intermediate muscular layer, serve to bound shallow spaces lying in horizontal strata, each of which, with its content, corresponds to a column of the *Torpedo*

organ. Fine septa, parallel with the plane of the cross-section (" transverse partition walls "), produce from the lateral aspect a delicate cross-striation of the single prisms, and divide them into closely-compressed narrow compartments, in each of which an " electrical plate " is supported at right angles. The form of this compartment, and of the plate within it, may in general be described as rectangular, with greater or less diminution towards the centre.

The average width of the compartments in the organ of *Gymnotus* is about $\frac{1}{10}$ mm., agreeing with the older observations of Hunter, who reckoned about 240 transverse septa to the English inch, *i.e.* about 0·1058 mm. width of compartment. In *Torpedo* it is about $\frac{1}{50}$ mm. The distance between the two longitudinal septa (height of compartment) is of course much greater. It is about 0·64 mm. in *Gymnotus* (Hunter). The total

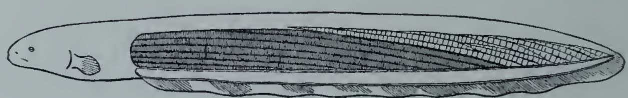


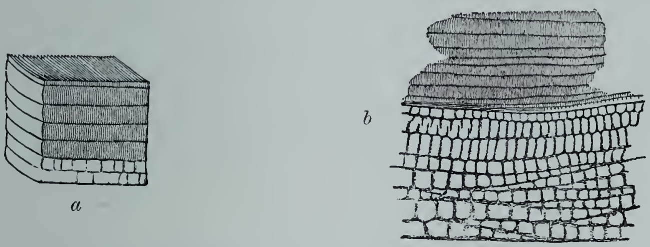
Fig. 239.

number of compartments lying between two longitudinal partition walls, with the band-shaped plates which they contain, may again be described as " columns," analogous with the prismatic columns standing at right angles to the body superficies in the organ of *Torpedo*. The columns of the large organ spring collectively (as shown by the lateral schema, Fig. 239) from behind and below the intermediate muscular layer, and ascend at a sharp angle above and in front. Only the foremost run approximately parallel with the axis of the fish.

Even to the unaided eye a certain part of the two large organs exhibits peculiar characteristics; *i.e.* it is darker, more transparent, and of a yellow-gray or pinkish colour, instead of being white like alabaster. This is because (as Pacini, 25, showed, Fig. 240, *a*, *b*) there are, along with the ordinary columns with small compartments, others in which the spaces are very wide. Sachs confirmed these observations. The " Sachs' bundle of columns," which he was inclined to regard as a new electrical organ in *Gymnotus*, lies as a rule above the posterior half of the large organ. It begins anteriorly in a fine point

(Fig. 239), increasing posteriorly, so that it soon occupies the upper half of the total diameter of the organ, and finally pushes its way completely behind the large organ. A section parallel with the long axis of the fish shows a general fusion of the longitudinal septa between the wide-spaced columns, which end before and behind in sharp wedges (Fig. 240, *b*); the cross-section is spindle-shaped, or rhomboidal.

If a longitudinal section of the electrical organ (parallel with the axis of the organ, and vertical to the long partition walls) is examined under a high power, it is easy to see the cross-sections of the transverse septa of connective tissue, extended between each pair of longitudinal partition walls, together with the compartments which they enclose, each containing a transversely



a *b*

Fig. 240.—*a*, Portion of several superposed prisms of *Gymnotus* (two wide compartments below). (Pacini.) *b*, L.S. through prisms of *Gymnotus*, wide and narrow compartments. (Du Bois-Reymond.)

bisected electrical plate (Fig. 241). With regard to the position and mode of attachment of the latter, there is a fundamental difference between Pacini and M. Schultze (31), as appears from the two figures (241, *a*, *b*). While Pacini holds that the plates depend freely in the compartment, and are attached only at the longitudinal septa, Schultze maintains that each transverse partition wall (*Q*) coheres with the posterior surface of the corresponding plate, so that there is a space only in front of, and not behind it. Both anterior and posterior surfaces of the plate are thickly set with papillæ ("villi," M. Schultze), behind which there are posteriorly, thorn-like processes (*prolungamenti spiniformi*, Pacini), which extend to the posterior partition wall, and are attached there. Schultze failed to discover the latter, while Sachs confirmed the observations of Pacini, as also for the cleavage of the plates (as observed by the latter), into an anterior and a posterior half. He regarded the papillæ with their so-called " nuclei " (known later

on as star-cells) as "cells," distributed over the anterior and

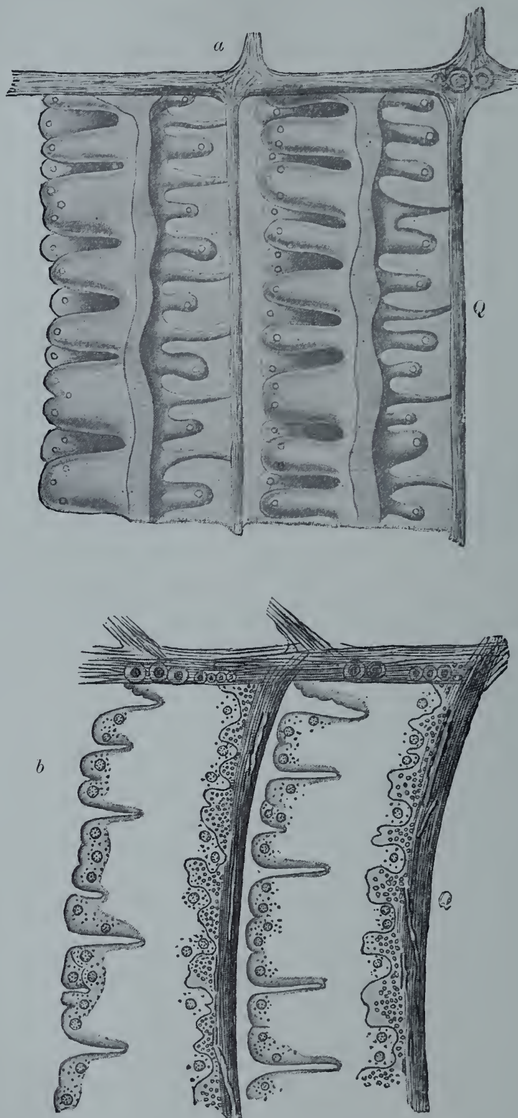


FIG. 241.—Two electrical plates of *Gymnotus*; L.S. of the organ (as in Fig. 240). (*a*, Pacini; *b*, M. Schultze.)

posterior surfaces of a ground-membrane (*parte fondamentale*,

Fig. 241, *a*). According to Sachs, the transverse section of the electrical plate exhibits the following layers from the front, posteriorly (Fig. 242). Next to the anterior papillar layer (*stratum papillare anterius*) comes a clear and perfectly structureless stratum, termed by Sachs the intermediate layer (*stratum intermedium*), corresponding essentially with Pacini's *parte fondamentale.* This is succeeded by the nervous layer (*stratum nerveum*), which, apart from the processes of the posterior star-cells which traverse it, is of a homogeneous gray colour. It gives off the posterior papillæ, and the thorn-like papillæ, forming collectively the *stratum papillare posterius.* The electrical nerves end at the nervous layer, as will be described below. Transparently homogeneous in the fresh state, the papillæ become granulated within even 1–2 minutes after removal from the living animal, while a sharp boundary line (*PL*) appears inside the intermediate layer, dividing it into two tolerably equal halves. Cleavage of the plate usually occurs at these "Pacinian lines," which appear in osmic preparations as a sharp dark streak in a broad, light zone. Sachs found "a substance resembling spider-web" between the anterior papillæ, "consisting of meshes of fine threads with small nuclear-like structures." Pacini detected nerves upon the transverse septa only, where Sachs also noted them plentifully, but in addition discovered their terminal branches between the thorn papillæ, and traversing the posterior cavity of the compartment, to end finally, after loss of the medullated sheath, in the plate itself.

FIG. 242.—T.S. of electrical plate of *Gymnotus;* L.S. of organ. (Sachs.)

The posterior surface of the plate exhibits in transverse section (with osmic preparations) the striation (or punctuation as

seen from the surface) first described in detail by Boll for *Torpedo.* The nerve-ending itself presents, according to Sachs, a varying aspect "resembling now Kühne's end-plate, and now Schultze's net." According to Fritsch, the thorn-like papillæ are to be viewed as the real bearers of the nerve-endings in the *Gymnotus* plates. "Upon these there are comparatively coarse prolongations of the axis-cylinder," so that they are "allied to the stalk of the *Malapterurus* plate." As regards the indisputable genetic relation between the electrical organs and striated muscle, it may be conjectured that the mode of ending of the nerve in the substance of the plate is analogous to that of *Torpedo,* although the observations made up to this time afford no positive evidence of it. The plates in the wide compartments of Sachs' columns are distinguished from the others mainly by the greater length of the anterior papillæ (Fig. 243), in which, moreover, in the fresh state, Sachs observed a broad, dim cross-striation and traces of double refraction, in the axis or at the margin.

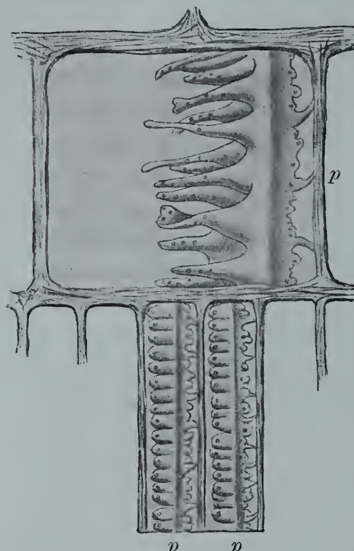


FIG. 243.—One wide and two narrow compartments of *Gymnotus,* seen in cross-section (as in Fig. 241) under a high power, with enclosed plates (*p*). (Du Bois-Reymond.)

If the final distribution of the nerve in the peripheral organ (electrical plates) is thus uncertain, no such doubt exists as to the central origin and coarser anatomical structure of the electrical nerves.

Valentin, reasoning from a likeness (afterwards proved to be inadequate) between the brain of *Gymnotus* and that of the eel, assumed a certain section of it (by analogy with *Torpedo*) to be the electrical lobe, and centre whence spring the electrical nerves. Later investigations, however, showed the part of the brain in question to be identical with the cerebellum so markedly developed in the allied cat-fish (*Silurus glanis*), the spinal cord being the immediate seat of origin for the electrical nerves. Max Schultze first pointed out the very numerous and large ganglion-

cells in the spinal cord of *Gymnotus*, and showed that there were twice as many as in other fishes, indicating a probable relation with the electrical nerves that pass out from this region. Du Bois-Reymond also concludes " that there must be a similar structure in the cord of the electrical eel to the *lobus electricus* of the electric ray." This is the more probable since the electrical organ of *Gymnotus* is supplied by intercostal nerves, which are so numerous as to have excited attention from the time of Hunter. Fritsch's thorough investigation of the materials brought by C. Sachs from Calabozo showed in point of fact that at a certain level of the cord, which is differently localised according to individual variations (12–23 vertebræ), large ganglion-cells, highly characteristic in their entire habit, appear at first singly, and later on as a closed column, in the form of a cylinder, surrounding the central canal, and open anteriorly; these must undoubtedly be denoted " electrical cells." " They exhibit the usual multipolar characteristics of well-nourished finely-granulated protoplasm, drawn out into several broad processes and bladder-like nuclei, with conspicuous, strongly-refracting nucleolus." The size of the rounded cell-body, which is invariably drawn out into a well-marked axis-cylinder process, is on an average 0·051 mm. The ordinary motor cells exhibit a more polygonal form, with better developed protoplasmic processes. No sharp division can, however, be predicated, since, according to Fritsch, there are transitional forms at the level of the 6–16 cervical vertebræ. At about the 30th vertebra the quantity of electrical cells has increased so much " that the entire cavity of the anterior horns, and central mass of the gray matter, seems to be filled with them, and they even cause a thickening of the spinal cord in the sagittal direction. It is only in front of the central canal that the cells do not meet, on either side, so that the cell-group in cross-section resembles a wide half-moon " (Fig. 244). " Here, where the seat of origin of the electrical nerves appears most fully developed, the axis-cylinder given off from the cells forms at each cross-section a distinct group of fibres, which run very obliquely. These coincide in arrangement and mode of origin with the ordinary anterior roots of other bony fishes. There are no special motor roots in the cord of *Gymnotus* alongside of the electrical, but the fibres from which the muscular nerves originate, succeed immediately upon the electrical nerves (Fritsch). Corresponding with the

fact that the electrical organs of *Gymnotus* extend to the tip of the tail, we find ganglion-cells of the electrical type as far as the end of the spinal cord, but they gradually diminish in number and size, and more nearly resemble in form the ordinary motor cells of the anterior horn.

While in these cases we have in *Torpedo* and *Gymnotus* electrical organs of such high differentiation that even the most powerful effects seem *ab initio* to be accounted for, there are in the tail of the common Skate (*Raja*), as well as in the species of *Mormyrus*, organs that in structure and arrangement are unmistakably allied with the electrical, but of which the effects are so slight that they have only recently been determined. These du Bois-Reymond named "pseudo-electric" organs. This distinction is, however, obsolete, seeing that both *Mormyrus* and the various species of *Raja* belong to the true electrical fishes, so that, as Babuchin expresses it, "there are no pseudo-electrical fishes, but only large and strong, or small and weak, electrical fishes, severally."

FIG. 244.—T.S. through the spinal cord of *Gymnotus electricus*. (Fritsch.)

As James Stark was first to discover, the electrical organs in the tail of *Raja* lie on either side, near the vertebral column, as two cylindrical, grayish, transparent bodies, pointed anteriorly and posteriorly. "They begin at the centre of the sacro-lumbalis muscle, near the junction of the anterior and second thirds of the tail, become gradually thicker, and, after completely displacing the muscle, lie close under the skin, where they are as thick as the muscle itself, and extend as far as the extreme end of the tail" (Fig. 245, *a*, *b*). Their position is shown even better in transverse than in longitudinal section (Fig. 246). Here the composition out of single, concentric "columns," running parallel with the axis of the tail, and separated, as in *Torpedo* or *Gymnotus*, by septa of connective tissue (M. Schultze's "primary partition walls," 31 *a*), is very obvious. Each column again breaks up by

numerous ("secondary") transverse partitions, set vertically to the long axis, into single, flat, quadrilateral chambers or compartments, lying one behind the other, and enclosing the true electromotive elements of the "plates" (Kölliker's "spongy bodies"). It appears from even superficial consideration of a long section that the single longitudinal columns of the electrical organ have in some degree replaced the involuted, cone-shaped muscle-segments, so that the primary septa are in part only a restoration of the tendinous partition walls of the sacro-lumbar muscles, and, like

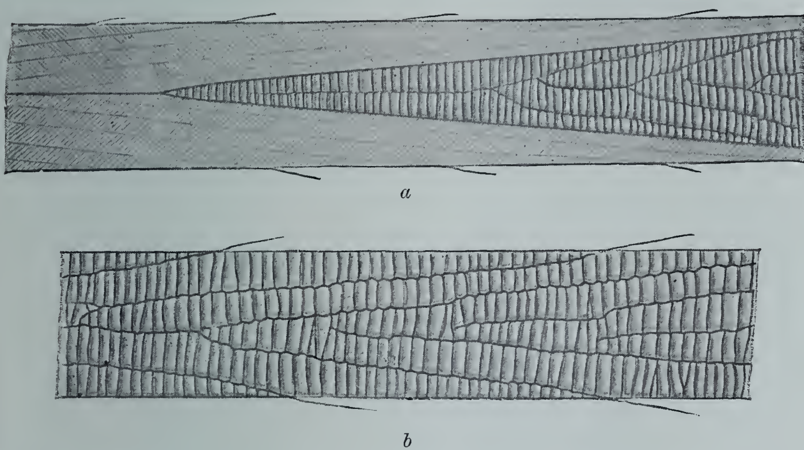


Fig. 245.—*Raja clavata:* L.S. of electrical organ in the tail. *a*, Anterior end, lying between the layers of *M. sacrolumbalis* (magnified three times); *b*, from the centre of the organ; the electrical plate lies at the anterior wall of each compartment. (M. Schultze.)

these, form cones with pointed anterior ends, fitting parallel into one another (Fig. 245). Fig. 247 gives a good representation of the arrangement of the single compartments within the columns, as well as the position of their contents.

These figures show that the comparatively thick plates, which are irregularly bounded on the posterior side, are attached to the anterior wall of each compartment, and occupy about one-third of the available inner space. Under a higher power the plates are seen (Fig. 248) to be surrounded by gelatinous connective tissue, which fixes them within the cavity of the compartment. The nerves to each compartment travel, as Kölliker (16) showed, from the anterior wall to the anterior plane, or goblet-shaped surface of the plate, forming by rapid division a rich plexus of non-medullated fibres. The true mode of ending is of course

only to be found on the surfaces of the plate, *i.e.* at the cross-section of the columns, but it has not yet been accurately determined. M. Schultze (*l.c.* p. 201) describes a net with narrow meshes, applied almost directly to the anterior surface of each plate. It is set with numerous nuclei, and is further

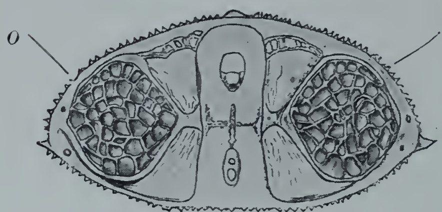


FIG. 246.—T.S. of *Raja batis.* O=T.S. of the organ. (Burdon-Sanderson and Gotch.)

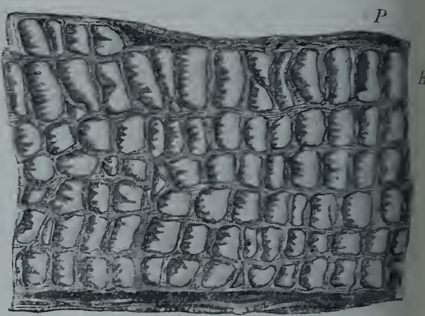


FIG. 247.—L.S. through electrical organ of *Raja batis.* K = compartment; P = electrical plate. (Burdon-Sanderson and Gotch.)

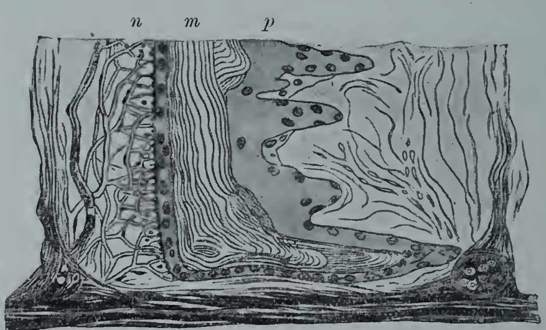


FIG. 248.—*Raja batis.* Part of a compartment with cross-section of enclosed plate (L.S. of the organ). n=nervous layer; m=meandering layer; p=papillary layer (alveolar layer). (Burdon-Sanderson and Gotch.)

continued posteriorly into a much finer network, exhibiting as a whole the same characteristics as the net described by Schultze and Kölliker in the *Torpedo* plate, and fuses directly with the substance of the plate. Babuchin failed to assure himself of the existence of this net, and Burdon-Sanderson and Gotch (13 *c*, p. 142) were uncertain as to the exact mode of ending. Beyond the nucleated zone into which the nerve expands, there is at the cross-section of the plate a tolerably thick layer without laminæ (meandering layer), the single strata of which lie parallel with

and horizontally over each other (*R. batis*), or are much bent and undulating (*R. circularis*). In immediate contact with this is a stratum that is frequently drawn out into papilliform processes, similar in character to the nucleated zone which invests the anterior surface of the entire plate, and forming the *posterior* border of the plate; this consists of a finely-granulated mass of protoplasm richly set with nuclei.

Recent investigations of Fritsch (12 *i*) have contributed to our knowledge of the structure and innervation of the *Mormyrus* organ. Here, again, there are compartments of connective tissue filled with gelatinous substance, and containing plates; but the finer structure seems to differ in many points. The nerve enters by means of special prolongations of the plates, which are club-shaped, and terminate in a conical, pointed form (" cones "), which Fritsch compares with the expanded motor end-plate of muscles.

In *Mormyridæ*, as in *Torpedo*, the fibres of the electrical nerves (corresponding with the situation of the organ in the tail) " are broad, unbranched axis-cylinder processes from large ganglion-cells, which at given parts completely fill up the gray matter of the spinal cord, and then leave the central organ as the anterior roots. Fritsch makes the important observation that the huge protoplasmic processes of these parent cells form a number of short, broad anastomoses, so that the electrical ganglion-cells, which form by actual *continuity* a narrowly circumscribed complex, are, as it were, bound up by a common function. Fritsch rightly lays stress on this observation, since on the one hand it shows the undoubtedly nervous character of these protoplasmic processes, while on the other it indicates the possibility, and, indeed, probability, of a similar course for the finest arborisations of motor nerve cells of the spinal cord in other vertebrates.

Even from a more anatomical investigation of these " pseudo-electric organs," it cannot be doubted that they are homologous with striated muscles, and formed by the gradual transformation of the latter. A glance at the tail of *Mormyrus cyprinoïdes*, when skinned, will reveal this, even to an unpractised eye. At a certain point, *i.e.* near the end of the anal fin, the regularly-arranged and flattened tendons of the caudal muscles suddenly lose their solid, fleshy attachment, as described by Fritsch, and stretch superficially across a transparent gelatinous mass, the

discoid structure of which at once betrays it as an electrical organ (Fritsch). It is more difficult to prove the muscular origin of the electrical organ in the *Torpedinidæ* and in *Gymnotus*. The evidence must be sought in the developmental history, and in comparative anatomy.

Torpedo is peculiarly adapted for the study of ontogenetical development. "This viviparous fish bears its young within itself to an advanced stage of growth, so that the newly-born fishes are already 6–8 cm. long, and able to give distinct electric shocks" (Fritsch).

The best observations in this department of anatomy, with its important physiological bearings, are those of Babuchin (1), and more recently Fritsch (12); de Sanctis having previously given an erroneous description of the development of *Torpedo*. Ewart (10) and Engelmann (8) have contributed further data of importance to the "pseudo-electrical" organ of *Raja*.

With regard to the development of the external form of the body in *Torpedo*, de Sanctis distinguishes three main stages, squaliform, rayiform, and torpediniform. At the end of the first stage the position of the electrical organ can already be recognised externally; swellings—which soon fuse together—make their appearance upon the visceral arches at the point where these bend to the ventral side. As soon as the trunk widens, the embryo assumes the form of the common ray (*stadium rayiforme*), and the continuous forward progression of the discs at last completes the characteristic rounded form of the electrical ray. At this stage the electrical organ of the then developed, but still unborn, fishes exhibits under the lens a delicate punctuation—the indications of the already perfected column (Fritsch).

At a very early stage in the development of the gill-arches, as described above, these appear to consist of bundles of elongated cells, invested by others of a rounded, embryonic character, and in all respects similar to embryonic muscle-fibres. The delicate cross-striation may be recognised *in situ*, still better on the isolated fibre (Fig. 249, *a*). The fibres, which are at first small, containing only one or two nuclei, bear many nuclei later on, and swell up at the ventral end, where a multitude of nuclei are formed by rapid division, and lie all together, while the plasma surrounding the terminal part increases in bulk, and exhibits a

kind of swelling (Fig. 249, *b*, *c*, *d*). The whole is suggestive "of a tassel, hanging from a loop set with knots (muscle-nuclei)" (Babuchin). Striated fibrils from the fibres of the trunk extend into the bladder-like swelling, described by Babuchin, on account of its being the initial stage of an electrical plate, as the plate-rudiment ("*plattenbildner*"). Fritsch defines them as "young

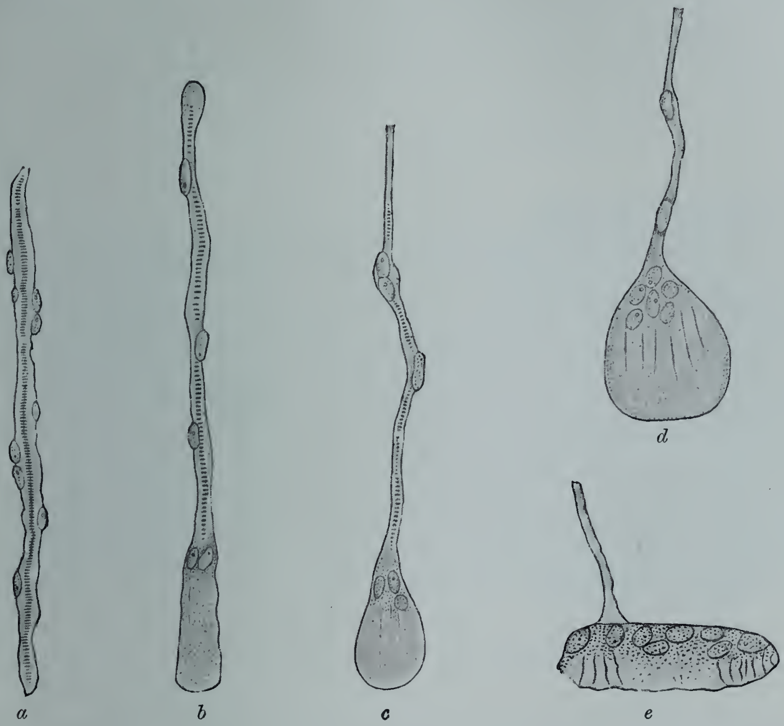


FIG. 249.—Development of the electrical plates of *Torpedo* from embryonic muscle-fibres. (Babuchin.)

plates," since with continued growth they are transformed directly into the final structure, and he believes that the characteristic pear-shaped form of Babuchin's figures must be referred to the swelling effect of the macerating methods employed. He himself, like Krause (17), finds them more loaf-shaped. The unequal length of the single muscle-fibres, which form the foundation substrate of a column, causes the plates to be of different heights in longitudinal section (Fig. 250).

"The non-swollen section of the muscle-fibres always remains at the same stage of embryonic development, and finally forms a

long, narrow, still plainly striated stalk to the plate-rudiment, which has meantime increased considerably in breadth owing to proliferation of nuclei. Its ventral half consists of an almost transparent plasma traversed by little fibres (muscle-fibrils?), while the characteristic rounded nuclei lie in a finely granulated dorsal stratum (Babuchin, Fig. 249, *e*). An isolated column at this stage consists of thick loaf-shaped bodies, not perfectly regular, and separated by embryonic cells. These do not take up the entire width of the column, but lie near and over each other." The stalks (remains of primitive muscle-fibres) are often attached laterally to the plate-rudiment, and become steadily thinner, subsequently disappearing altogether, while the latter now finally assume the shape of very thin plates, and fill up the entire cross-section of the column. Isolation of the plates is very difficult at this stage, seeing that the external border cells gradually coalesce into a firm sheath of connective tissue round the electrical prisms. Little as the structure of a complete column of *Torpedo* recalls a striated muscle structure, there cannot, in view of the above facts, be the slightest doubt as to the genetic relations between the two tissues, and one of the most significant advances, not merely in the anatomy, but also in the physiology of the electrical organ, was the discovery by Babuchin of this connection. As Engelmann remarks (8, p. 149), "Nowhere else in nature have we, side by side, and so completely accessible to research, the anatomical and physiological factors for the vital production of mechanical and electrical energy."

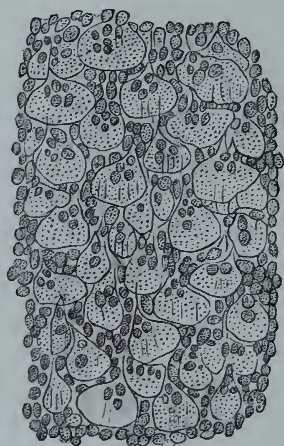


Fig. 250.—L.S. of embryonic column of *Torpedo*. p = rudiment of plate. (Babuchin.)

Unfortunately all attempts made by C. Sachs to determine the embryonic development of the organ of *Gymnotus* were fruitless, and we can only conjecture that it occurs in the same way, generally speaking, as in *Torpedo*.

In the Ray, on the other hand, there is no doubt as to the very interesting development of the less highly differentiated pseudo-electric organs.

Here we no longer have undeveloped embryonic muscle-fibres, but such as are completely differentiated, striated, and capable of functioning, from which, "at a late moment of post-embryonic life," a special modification gives rise to the elements of the electrical organs.

It can be demonstrated in all certainty that the meandering layer of the plate, as described above, is directly derived from the striated substance, more especially in *Raja radiata*, where, as Ewart shows, it has the appearance of normal striated muscle

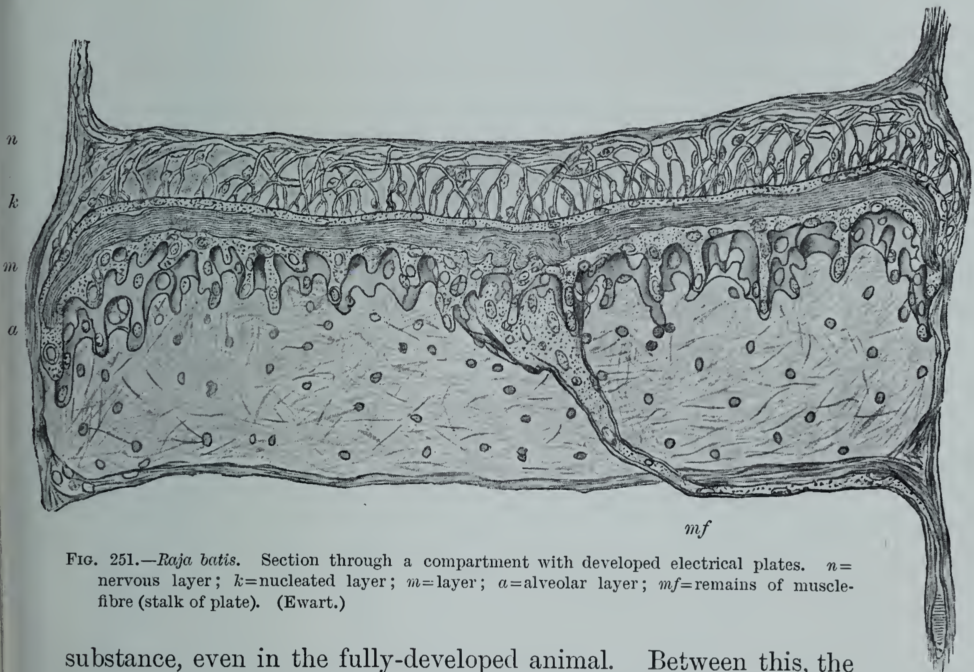


FIG. 251.—*Raja batis*. Section through a compartment with developed electrical plates. *n*=nervous layer; *k*=nucleated layer; *m*=layer; *a*=alveolar layer; *mf*=remains of muscle-fibre (stalk of plate). (Ewart.)

substance, even in the fully-developed animal. Between this, the phylogenetically lowest, to the highest forms, which are distinguished by a complicated meandering course (*R. circularis, batis*), there is every possible transition.

As has been said, each single plate of *Raja batis* consists, apart from the surrounding connective tissue and ingoing nerves and vessels, of an anterior stratum of plasma with embedded nuclei, which is very probably homologous with the motor end-plates of striated muscle, and in which the numerous and at first dichotomously branching nerves terminate.

Then follows the non-lamellated layer, of parallel striation in

cross-section; and finally the "alveolar" layer, once more richly set with nuclei, which Ewart (10) aptly compares with the bayed inner wall of the frog's lung. From this layer there is, moreover, a long stalk-like process which extends backwards through the mucous tissue of the compartment, and ends in the connective tissue wall of the chamber (Fig. 251).

In very young embryos of *R. batis* there is no trace of any electrical organ as such. It is only at a length of about 7 cm. that a horizontal longitudinal section through the tail exhibits, between the ordinary normal fibres, others which must be regarded as in the first stage of transformation into electrical plates (Fig. 252, *a*). This is at first shown only by a club-like swelling of the anterior end (where a nerve enters with copious bifurcation), and a striking proliferation of nuclei, resulting finally in a sort of end-plate or cap, with which the head of the club is invested. The further stages of transformation are intelligible without more description from the figures (Fig. 252, *b*, *c*, *d*), drawn from preparations from an older embryo 10 cm. long. Here it is easy to recognise all the essential parts of the developed electrical plate—the nucleated nerve end-plate at the top, the non-nucleated, striated meandering layer, with its undoubted relation to the original cross-striation of the muscle-fibre, and lastly the alveolar stratum (*e*, *f*) derived from an exuberance of the sarcoplasm and (muscle-) nuclei at the base of the club, with the tail-like appendage of the atrophied stalk of the plate as the remains of the original fibre. This long exhibits indications of cross-striation, and may under certain conditions be detected even in the perfectly developed plate.

The electrical organ of *R. circularis* is longer, but much smaller. It consists of curved goblet-shaped plates, corresponding essentially with those in *R. batis*, where there are already indications of a goblet-like pitting of the initially club-shaped and swollen ends of the muscle-fibres.

The approximately parallel lamellæ of the meandering stratum in *R. batis* are much curved in *R. circularis*, and the alveolar layer also exhibits a different structure, and presents a fine radial striation at its base (Fig. 253). The first trace of a transformation of muscles into electrical tissue is, however, ascribed by Ewart to *Raja radiata*, as shown on the one hand by the much later commencement of the process, on

the other by the obvious cross-striation of the fully-developed plates.

The important question of homologies between the lamellæ of

a *b* *c*

FIG. 252.—*Raja batis*. *a*, Portion of a longitudinal section through an embryo. Club-shaped muscle-fibres developing into electrical plates. *b-f*, Further stages of development. (Ewart.)

the matured laminated layer, and the transverse striæ of muscular fibres, was till recently quite undecided. The careful investigations of Engelmann have thrown some light on the subject.

Exact comparative observation of the different stages in the development of the organ in *Raja clavata* in the same embryo,

d *e* *f*

$7\frac{1}{2}$ cm. in length (Fig. 254, *a–e*), leaves no doubt that both the small, dark, and the broad, clear, transverse striæ of the original

muscle-fibres correspond with the similar cross-bands in the lamellar stratum of the fully-developed plate. Not merely preparations at different stages, but the same individual fibre will present every transition from the "typical striated muscle substance, to the typical meandering stratum of the perfect electrical organ." Still plainer is the homology between the thin, strongly-refractile lamellæ of the electrical organ and the arimetabolous (isotropous) layers, and that of the thick, weakly-

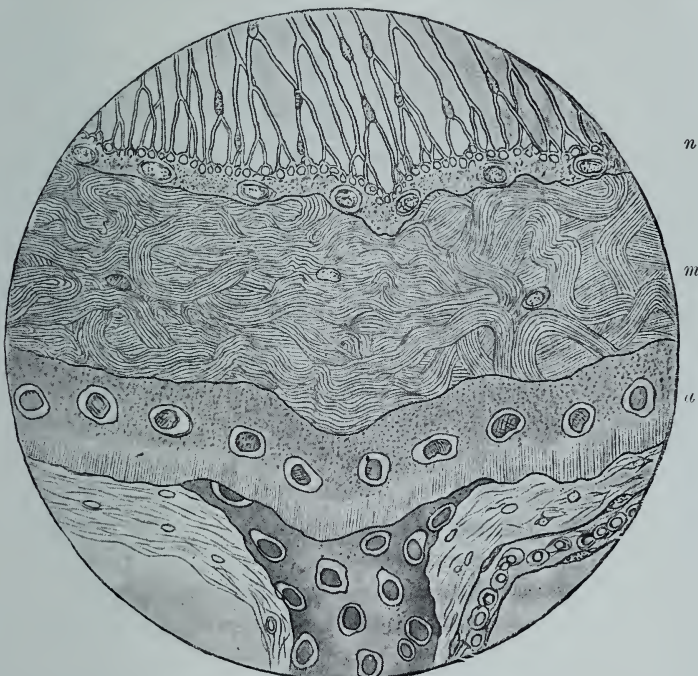


Fig. 253.—*Raja circularis.* Portion of L.S. through an electrical goblet. n=nervous and nucleated layer; m=meandering layer; a=alveolar stratum. (Ewart.)

refractile lamellæ, with the metabolous (anisotropous) layers of striated muscle, under a very high power. In this process of transformation, the superficial growth of the lamellæ increases vertically to the fibre-axis on the one hand in a marked degree, while on the other the height of the layers also increases doubly and trebly. Along with this there are fundamental alterations in the morphological and physico-chemical reaction of the two layers, expressed above all in polarised light by the marked diminution in double refractability, which "in the metabolous layers becomes

almost imperceptible, before any other alteration due to the transformation can be discovered." The strong surface-growth of lamellæ depends (as Engelmann showed), previous to the formation of loculi, essentially upon multiplication of the fibrils at the periphery of the lamellæ, not upon the thickening of those which

Fig. 254.—*Raja clavata.* Successive stages in the development of an electrical plate from a cross-striated muscle-fibre. (Engelmann.)

already exist, or upon the widening of the inter-fibrillar spaces. Later on, in the perfected organ, no fibrillated structure of the lamellæ can be detected.

If the optical alterations in the series of strata during the development of the electrical are compared with those seen in vigorous, physiological contraction, there are striking coincidences, as pointed out by Engelmann. On the one hand, the arimetabolous

(isotropous) lamellæ become "optically more homogeneous, more strongly refracting on the whole, and therefore firmer (less watery)," while on the other the metabolous strata (particularly those of the transverse discs) lose in refractability, which simultaneously diminishes their power of double refraction. The amount of this diminution is, however, "*nil* in contraction, as compared with that in the transformation of muscle-fibres into the meandering layer of the electrical compartments." It is, moreover, apparent at such an early stage of development (previous to the club-shaped swelling of the proximal end of the muscle-fibre) that no other sign of approaching transformation can yet be detected. At this point, again, the phylogenetically younger status of the organs of *Raja radiata* is apparent, since the double refractility here disappears much more slowly and incompletely than in other kinds of the same species (*R. batis, clavata, circularis*). This reaction during the transformation into electrical organs gives substantial confirmation to Engelmann's conjecture that "only the doubly-refracting metabolous elements of the muscle-fibrils are the seat and source of the contractility of the muscle."

The development of the "pseudo-electric" organ in *Mormyrus* is much less certain than that of *Raja.* Yet here, too, Babuchin (1) was able, on investigating six varieties of the species, to state definitely that "the electrical organs are again developed from muscles, and retain their muscular characteristics even when the formation is perfect." Each "plate" of *Mormyrus* consists of three laminæ that can be separated from one another, the two outer being "structureless, invested from the inner side with a layer of granulated substance, and set with numerous rounded nuclei." One of these laminæ is the immediate prolongation of the sheath of the pale (ingoing) nerve-fibres. The middle layer consists exclusively of very thin flattened muscle-fibres or bands, lying irregularly near each other. Each single fibre is sharply striated, while collectively they form a muscular lamina of firmer consistency towards the border of the electrical plate than in the centre, with no meandering markings. According to Babuchin, therefore, the electrical plate of *Mormyrus* does not correspond ontogenetically with a *single* metamorphosed nerve-fibre, as in *Torpedo* or *Raja,* but with "an entire bundle of short muscle-fibres, as found in the lateral trunk-muscles of fishes."

Fritsch (12), too, affirms that a tissue of varying density is

visible in fine transverse sections of *Mormyrus* plates, "which preserves the complicated cross-striation of the muscle in an extraordinary degree." This forms the middle stratum of each plate; the anterior exhibits a delicate longitudinal striation (analogous to the palisade border of the *Torpedo* plate), beneath a fine cuticular border.

If it is thus certain that the electrical organs so far described are to be viewed collectively as transformed, and specially differentiated, striated muscles, the most superficial anatomical comparison serves on the other hand to show that quite different groups of muscles are in each several case the starting-point of this marvellous process of differentiation. Thus in *Torpedo* the external layer of the small muscles of the bronchial apparatus, and the external muscles of the jaw which are so marked in the allied ray, are wanting; in *Gymnotus* the deepest part of the ventral trunk-muscles, save the small remnant known above as the "intermediate muscular layer," is transformed into the *large* electrical organs, while the *small* organs are derived from the upper part of the inner muscles of the fins. In *Gymnarchus,* again, the electrical organ corresponds with the central portion of the lateral muscles, while in *Mormyrus* and *Raja* the parts of the caudal muscles adjacent to the lateral lines afford the material of the "imperfect" organ. The appearance of the electrical organ is not therefore confined topographically to any definite region, but *every group of muscles, the normal functioning of which is not indispensable to the existence of the individual, may be held as an adequate substrate for the development of an electrical organ* (G. Fritsch, 12).

If a transverse section through the trunk of *Malapterurus,* which, as regards its muscles, is nearest to *Gymnotus,* is compared with a similar section of the latter, it is easy on either side to detect the transverse sections of the four lateral trunk-muscles so characteristic of the bony fishes (*M. laterales proprii inferiores et superiores,* Fig. 255, *a, b* [*Ms*] and [*Mi*], and *M. laterales dorsales et ventrales,* [*md*] and [*mv*] of the figures). These, as shown more particularly from the lateral aspect, are divided segmentally in the long axis of the fish by the zigzag *ligamenta intermuscularia,* the single discs, each corresponding with a segment, being transformed into hollow cones, which are, as it were, inserted into each other. *Malapterurus* is distinguished from other bony fishes

by the appearance of a group of muscles, given off from the flat abdominal muscles, and beginning behind the shoulder-girdle. These diminish rapidly in size, and run as a clearly marked band of muscles below the lateral muscles proper, to the caudal end (*M. lateralis imus* [*me*], Fritsch). The lateral aspect further shows this strip to be distinctly curved towards the horizontal behind the *ligamenta intermuscularia*, so that the short bundles of primitive muscle-fibres stretched between them are presented as low, narrow compartments. It is easy, especially in cross-section, to see that the position of the large electrical organs

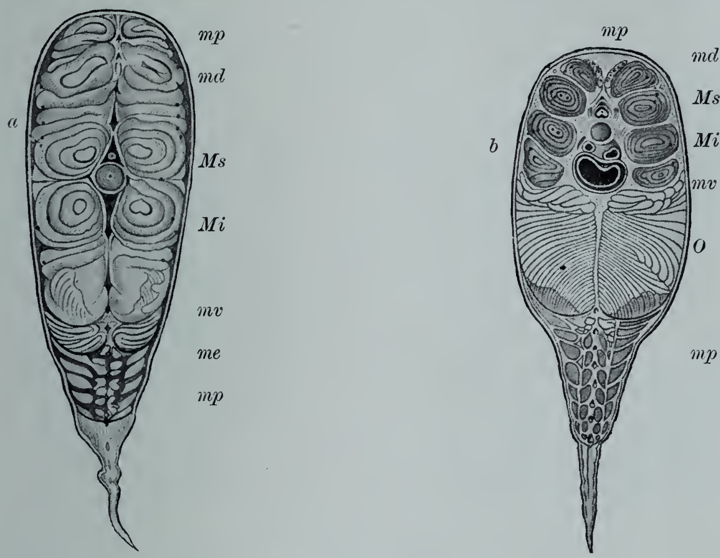


FIG. 255.—*a*, T.S. from tail of *Silurus glanis*; *b*, T.S. from the fourth ½ of *Gymnotus*. (Fritsch.)

of *Gymnotus* corresponds throughout with that of the band of muscle just described in *Malapterurus*, which is here wanting, and has by its transformation given rise to the organ. There is no less certain proof that the so-called *small* organ of *Gymnotus* has been formed by the transformation of a part of the lower muscles of the fins. In correspondence with the very scanty development of the dorsal fin, two small triangular sections of muscles only are left in the cross-sections of both *Malapterurus* and *Gymnotus*, beneath the skin of the back (Fig. 255, *a*, *b*, *mp*). On the other hand, there are, on the ventral aspect of the cross-section, on both sides from the median plane, two

systems of transversely-divided fin muscles (external and internal, Fig. 255 [*mp*]), which are especially numerous and well developed in *Gymnotus*, and increase posteriorly in number and extension. The small organ increases similarly in height, while the number of prisms in the large organ, on the other hand, decreases towards the caudal end, "since they become rolled up underneath, and leave the lateral surface of the body." In the region where the small organs are fully developed, the upper bundles of the deep fin muscles are wanting, so that the genetic relation between the two is unmistakable. So,

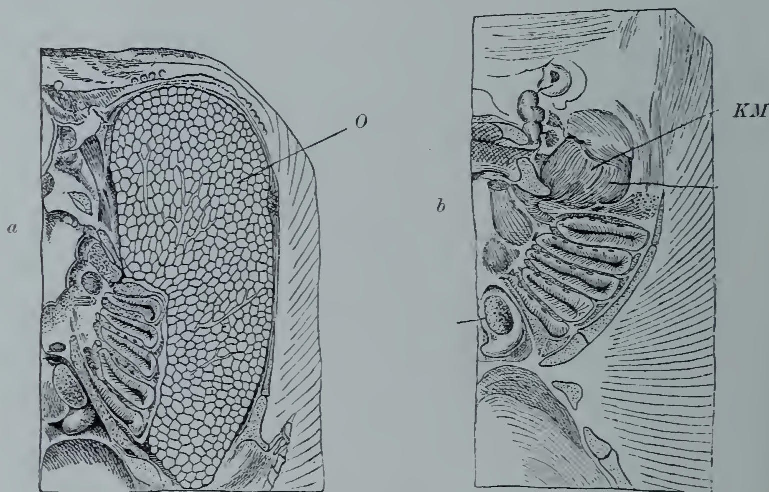


FIG. 256.—Homology between the electrical organs (*O*) of *Torpedo*, and the muscle of the common Ray (*KM*). (Fritsch.)

too, in the *Torpedinidæ*, where the powerful jaw muscles of the common ray (Fig. 256, *b* [*KM*]), which are balled into a clump, fail almost entirely, and are reduced to an insignificant vestige. This chiefly involves the external or ventrally-developed muscles of the gill chamber, representing the system of the *adductores arcuum* and the so-called *constrictor communis superficialis* (Fritsch), which here correspond functionally with the masseter, pterygoid, and temporal muscles. The constrictor seems more especially to have yielded the elements for the posterior part of the organ, while the broad, anterior portion seems to derive more particularly from the modification

of the adductor (Vetter, "Kiemen- u. Kiefer-muskulatur der Fische," *Jenaische Zeitschr.* VIII.).

As regards the developmental processes of the electrical organs, it is *a priori* improbable that the number of separate elements (plates or columns) should increase with the growth of the individual. Even in 1839 it was affirmed by Delle Chiaje "that the columns of the electric ray grow by intussusception (the same number being developed as exists in miniature in the embryo), merely by gradual increase in mass and size." R. Wagner in 1847 defended this statement against Valentin and Babuchin, extending it to the number of plates in the columns, and tracing it back to its embryological origin. This dictum of the *preformation of the electrical elements* makes the number of columns (and plates) in different individuals of the same species of electrical fishes to be approximately the same, whether the animals are examined young and small, or when fully developed.

Du Bois-Reymond (4 *e*, p. 403) put together in the following table (Table I.) all the estimates then made of the columns in the electrical organs of *Torpedinidæ.*

In these the calculation from the fœtus of *Torpedo ocellata* speaks very decidedly in favour of the above conclusion. The anomalous and divergent results of Valentin and Girardi, however, leave an uncertainty which at first drove du Bois-Reymond also to the conclusion "that the deposit of columns in different individuals of the same species was initially different, and did not alter subsequently." Marked deviations in number of columns, exceeding the range of individual variations (such as the cases cited by Hunter and Henle in the above tables), would of course, on the preformation theory, be ascribed to difference of species. Fritsch took the trouble to review the family of *Torpedinidæ* from this standpoint, and the following data (Table II.) give some examples from his numerous calculations (Fritsch, 12).

[TABLE

TABLE I. NUMBER OF COLUMNS IN THE ELECTRICAL ORGANS OF DIFFERENT TORPEDINIDÆ

Species.	Length.	Number of Columns in Organ. Left.	Single.	Right.	Experimenter.
	mm.				
Raja torpedo	1219	...	1182	...	Hunter
	457	...	470	...	
	...	...	420	...	Girardi
	...	...	480	...	
	...	520	...	514	
	...	290	...	265	
T. Galvanii	273	...	410	...	Valentin
,, (fœtus)	82	...	298	...	
T. marmorata	262	...	420	...	R. Wagner
	393	...	...	420	Leukart
	230	449	...	...	
Fœtus of T. ocellata	81	...	...	410	Leukart
With yolk-sack	...	...	400	...	R. Wagner
Narcine dipterygia	61	...	130	...	Henle

TABLE II. NUMBER OF COLUMNS IN ONE ELECTRICAL ORGAN OF TORPEDINIDÆ

Species.	Length of Fish.	Organ.	Number of Columns. Dorsal.	Ventral.	Difference.
	mm.	mm.			
Torpedo ocellata	121	37	487	491	− 4
,, marmorata	216	66	469	536	− 67
,, ocellata	161	68	406	...	...
,, ,,	335	98	379	404	− 25
,, ,,	373	114	396	426	− 30
,, marmorata	357	123	446	484	− 38
,, ocellata	405	128	404	436	− 32

From this it appears that the number of columns is not the same on the dorsal and ventral surfaces, but varies to a considerable extent. It is questionable whether this is due to a free ending of the columns within the organ (as is the case in *Gymnotus* also). In the sense of the preformation theory, on the other hand, the number of columns remains approximately equal, with variations in the length of the organ of 37–128 mm. The same appears from Babuchin's later calculations from a mother-fish 42 cm. long, and 3 embryos of $10\frac{1}{2}$ cm. long, with a gut

still filled with yolk. The number of prisms in these was 478, 467, 443, while in the former it was 471.

Species of *Torpedinidæ* (*T. marmorata, ocellata, panthera*) which are otherwise quite characteristic, exhibit only small and inessential differences in the number of columns. On the other hand, Fritsch confirms the strikingly small estimate (146) in *Astrape dipterygia,* already given by Henle, finding equally low numbers of columns in other species of *Narcine,* cf. *N. tasmaniensis,* New Zealand, 278; *N. lingula,* China, 274; *N. timlei,* 230; *N. indica,* 145; *Astrape capensis,* 147; and *Temera Hardwickii,* 139. On the other hand, there is an unusually large number of columns in a speckled degenerate type of *Torpedo marmorata* (var. *annulata*). Fritsch was able in Vienna to investigate two examples of the giant (152 cm. long) American *T.* (*Gymnotorpedo*) *occidentalis,* in which he found over 1000 columns (1037), so that it is natural to regard the example quoted above from Hunter as one of the same species brought to the English shores by the Gulf Stream. To this, the largest species extant, must be added, in view of the number of its prisms, *T.* (*Gymnotorpedo*) *hebetans* (Lowe), the only specimen of which, in the British Museum, contains 1025 prisms, although it is no larger than a medium-sized *T. marmorata.* The rare *T.* (*Gymnotorpedo*) *californica,* from the west coast of Africa, is equally distinguished by its small size and large number of columns.

It is much more difficult to determine the number of columns in *Gymnotus,* more particularly, according to Fritsch, in the posterior section of the body, which presents the greatest structural irregularities. The total sum of all the columns in the large organ seems, from Fritsch's investigations, to vary within a wide range, since it falls below 50 in some instances, while in others it is nearly 100. The greatest number is always found in the smaller individuals of *Gymnotus.* Whether this is due to arrested development, or to differences of sex, race, or species, cannot be decided.

The exact determination of the number of plates in the columns of the organ would be theoretically of great value; unfortunately the data are not satisfactory. "There are, on an average, 10 plates to the millimetre in the electric eel, and since the organs are about 80 cm. long in a medium-sized animal, 1 metre in length, this would give 8000 plates one behind the other, without reckoning the wide compartments of Sachs' bundle

of columns" (du Bois-Reymond). Valentin gives only 5150, Pacini only 4000. Hunter reckons 150 plates in a column 25·4 mm. long of a medium-sized ray; Leukart, 180; Pacini, reckoning the height of column at 40 mm., counted 2000 plates, while Valentin only finds about 300 plates in medium columns (of 11·3 mm.). The figures thus vary considerably, as is not surprising when one reflects on the difficulties of enumeration, even with the most favourable conditions of preservation. Fritsch (12 *g*, ii. p. 1105) estimates the number of plates in a column of *Torpedo* (*Fimbriotorpedo*) *marmorata* (length of body, 265 mm.) 13·5 mm. high, at about 375; since the organ contains 479 columns, the total number of plates would be 179,625; in *T. ocellata,* with an average column number of 433 (height of column usually 6·25 mm.) and a content of 380 plates, the sum total would be 164,540 plates. These measurements also bring out the further and striking point that "the plates are closer together in the lower than in the higher columns of the same organ," so that the growth of the latter is in this respect also "a process of swelling, leading to the divergence of the plates," which on growing increase in diameter, as found by Boll.

There is another method of determining the number of plates in the organ of *Torpedo.* If, as cannot be doubted, each fibre of the electrical nerve is to be regarded as the axis-cylinder process of a ganglion-cell of the electric lobe, it is evident that definite and regular relations must exist between the number of cells and the number of plates in the entire organ. If the total number of cells = N, these will, by means of the correlative N axis-cylinders, which each divide into 18 branches, and supply the 6 corners of each plate, innervate $N \times \frac{18}{6} = 3\,N$ plates. From this point of view the enumeration of ganglion-cells in the lobe is of great interest. After Boll had undertaken a research in this direction, estimating a number of 53,760 cells, which is far too low, Fritsch adopted the much safer method of counting the axis-cylinders in the electrical nerves by photographing sections of the four nerve-trunks. He obtained a total of 58,318 nerve-fibres, which on multiplying by 3 gives the number of plates as 174,964. This agrees with the number as given above at 179,625 sufficiently to justify the method.

The Electrical Cat-fish (*Malapterurus electricus*), the Raâsch of the Arabs, which inhabits many of the rivers of Central Africa, is an exception to the other electrical fishes, inasmuch as its powerful batteries are not due to the transformation of striated skeletal muscle-fibres, but are localised in the skin, which is in consequence transformed into a thick, transparent, speckled rind, which loosely invests the greater part of the trunk, and causes the animal to look bulky and shapeless. This peculiarity expresses itself internally in parallel folds of the skin, during sideway

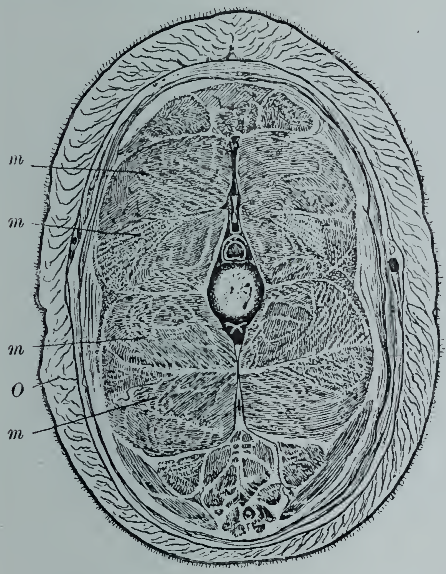


Fig. 257.—T.S. through trunk of *Malapterurus*. m=muscles; O=organs. (G. Fritsch.)

Fig. 258.—Particle of skin of *Malapterurus* seen from above; magnified. (G. Fritsch.)

movements of the body. In cross-section it is evident that this rind invests the body proper like a sack, and is separated from the muscular surface by an excessively loose tissue (the so-called integument of Rudolph), so that it is easily drawn off (Fig. 257). Between the epidermis proper and the internal, tendinous boundary of the rind there is in the fresh state a transparent, gelatinous mass of a clear yellow-gray colour, which is unequal in consistency, but entirely absent in a few places only. In the older specimens two longitudinal partition walls running dorsally and ventrally in the middle line divide the brawn-like intermediate mass symmetrically into two hemi-

cylinders surrounding the trunk on either side, and these represent the single, albeit bilaterally symmetrical, electrical organ, the weight of which, according to Fritsch, is more than one-third of the total body-weight. "Anteriorly it extends laterally as far as the pectoral fin, superiorly in a lobe-like prolongation to the region between the eyes, inferiorly to the anterior wall of the shoulder-girdle. Posteriorly; above to the origin of the dorsal fin, below to the origin of the anal fin." The diameter is greatest in the centre of the trunk, and a little in front of this, and gradually diminishes towards the anterior and posterior ends of the body.

The complete integrity of the system of skeletal muscles, both anatomically and as compared with all other electrical fishes, is very remarkable, and causes Fritsch to assume that the electrical organ has not in this case been differentiated from the muscles. Since it here arises wholly from elements of the skin, its structure must be described in detail.

Under the lens (Fritsch, 12 *f*) the wealth of small conical villi is especially remarkable, between the bases of which there are rounded openings leading into tubular pits in the epithelium. Around these there is a crowd of binuclear "club-cells" (Fig. 259), which function as unicellular glands, and are well developed from below, like those found in the skin of other fishes; these finally empty their contents into the adjacent epidermoid tubes. But in this case a special interest attaches to the club-cells, since Fritsch ascribes to them conjecturally "the same embryonic arrangement as the elements of the electrical organ." As we are completely ignorant of the ontogenesis of the latter, this is only a hypothesis, and must be left over for future investigation. It should be no matter of surprise if the elements (unicellular glands) next in electromotive activity to muscle were to prove capable of forming true electrical organs. For the rest, the epidermis of *Malapterurus* consists of ordinary epithelial cells (bristle or prickle cells) and a few goblet cells, *i.e.* on the side of the villi. As regards the finer structure of the organ, the first point that strikes one is the lack of any regular arrangement of the plates into "columns," as in *Gymnotus* and *Torpedo*. Nor can the brawn-like mass deposited from the skin of *Malapterurus*, and similar in consistency, when fresh, to the vitreous body, or to Wharton's salts, be compared with the imperfect electrical

organ of *Raja*, with its distinct series of cases. Closer inspection reveals in sections parallel with the surface of the skin, or with the axis of the fish, a delicate lattice-work of fibres, which cross at an acute angle, the intermediate spaces appearing grayish and semi-transparent. After treatment with a hardening reagent (alcohol, chromic acid) these structural relations are seen still more plainly. The lattice-work (" sieve," Bilharz) is then found to correspond with the cross-sections of innumerable fine membranes of connective tissue, which run vertical to the axis of the

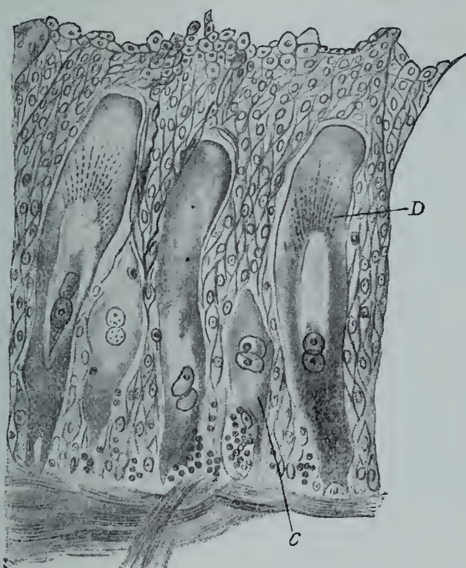


FIG. 259.—Portion of T.S. through epidermis of *Malapterurus*. (Fritsch.)

fish, separated by small intermediate spaces. These pass externally into the mass of fibres of the corium, while they unite internally into the so-called tendinous integument. In this way the organ is composed of innumerable partition-walls, running parallel with each other, but at right angles, collectively, to the axis of the fish, and divided into a number of small, hollow spaces, of approximately the same size, with no internal communication (Fig. 260). The axes of these compartments, which are mostly lens-shaped, or double pyramidal, all lie parallel with the axis of the fish. Their equatorial planes are thus vertical to the same, so that the one wall is turned to the head-, the other to the tail-end. Within

this compartment there is "a special, disc-shaped, integumental expansion," which Bilharz (3) was the first to recognise for the electromotive element proper, the terminal expansion of a twig of

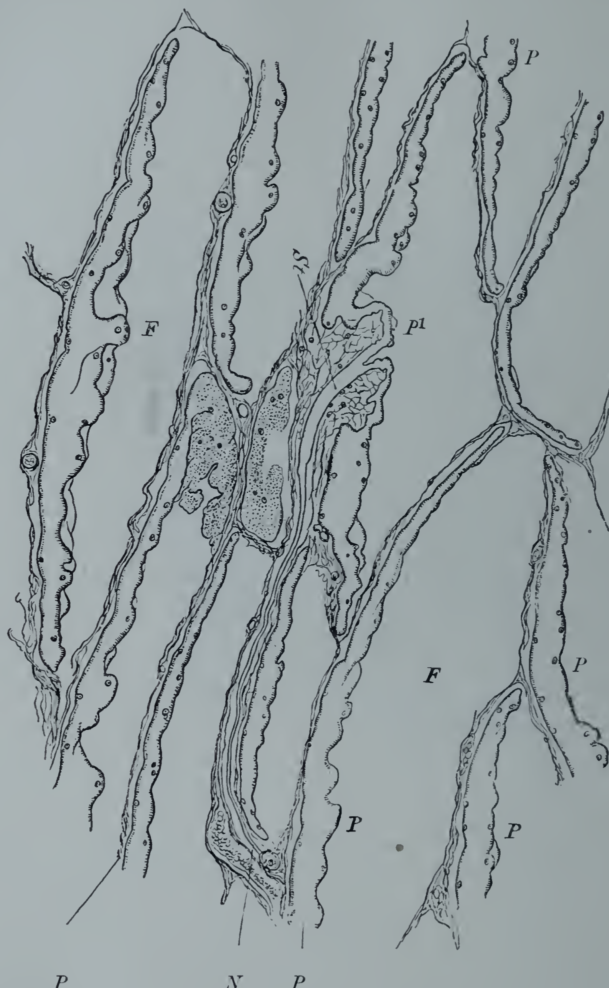


FIG. 260.—*Malapterurus electricus.* Portion of L.S. through the organ, showing the spaces (*F*) bounded by septa of connective tissue; an electrical plate is attached to each posterior wall (*P*); *N P*1 = plate with nerve-stalk. (Fritsch.)

nerve, *the electrical plate,* analogous in all respects with the many tissues of similar structure and composition in the other electrical organs. Each of these is attached to the posterior wall of its

compartment, while the anterior surface, presenting many inequalities, is free, and turned towards the head-end of the fish; it is separated by a small fissure filled with gelatinous substance from the anterior wall of the next compartment (Fig. 260). From the front aspect, each plate appears as a fairly circular disc, its central point being marked by a shallow prominence, giving origin to several high radial folds, while there is a corresponding depression on the posterior surface, from the foundation of which springs a kind of stalk connected with the ingoing nerve-fibre (Fig. 260, $N P^1$).

FIG. 261.—*Malapterurus.* Medium portion of a plate (*Pl*) with nerve-stalk (*ne*), under high power. (Fritsch.)

The substance of the plates, which increases in diameter with the size of the animal, is homogeneous and transparent in the fresh condition (Fig. 261). Rounded nuclei are embedded at regular and tolerably wide intervals, and were taken by Babuchin for star-shaped cells, with fine, hair-like processes. According to Fritsch, on the other hand, each electrical disc must be regarded as a multinuclear protoplasmic body, a kind of "giant electrical cell."

The marginal striation first observed by Remak on the plates of *Torpedo* occurs also on the discs of *Malapterurus*, and is ascribed by Fritsch to a peculiar porosity of the most external layer of the plate-substance (Fig. 261). The "rods" enclosed

between each pair of porous canals appear under a high power to consist of cemented lumps. Each disc is surrounded externally by a cuticular membrane which here and there may stand free of the anterior surface.

According to Fritsch, the construction of the electrical organ out of round discoid plates, which hang "like grapes on their stalks" from the stems of the finest nerve-branches, is seen most plainly in young animals, if a section is spread out in a hardening fluid (1 per cent osmic acid), the intermediate tissue being still relatively undeveloped. From this we may conclude that, in the embryo, "the elements destined to form electrical discs appear as a dense accumulation of cells, between which there is an indefinite intercellular substance, somewhat resembling the strata of unicellular glands, as found in the body-wall of many insects, even in the fully-developed state" (Fritsch). The regular arrangement so essential to function is developed later, and not at all in the peripheral parts of the organ. This is so constant that plates have been found at the posterior end of the organ, in the same or nearly the same plane as the body-superficies, *i.e.* at a right angle with those lying normally, or even in contact with their posterior surfaces. The inferior activity of the posterior half of the organ, as determined by du Bois-Reymond, is partly due to these irregularities of arrangement.

Fritsch also endeavoured to count the electrical plates in the organ of *Malapterurus* by calculations from sections of known length, multiplied into the total extension of the organ. He found "the number of the electrical discs contained in a longitudinal unit of the organ, as compared with those of another specimen of *Malapterurus*, to be in inverse ratio with the length of the organ in both cases," while in the same individual they are 20 per cent less numerous in the posterior than in the anterior sections. Fritsch estimates the total number of discs in the organ at about 2,000,000. "About 1600 lie in series from head-to tail-end, while a cross-section from the middle of the organ contains about 3000. One cubic centimetre of organ contains about 14,000 in a medium-sized specimen."

The whole innervating system of *Malapterurus* exhibits the same anomalies as the minute structure of its electrical organ, in an even higher degree. At the commencement of the spinal cord in the region where the first vertebra is connected with the *os occipitale*

basilare, a seemingly unpaired grayish bundle of nerves (Fig. 262, *ne*) appears from below, apparently from the lower (anterior) median cleft. This bundle at once divides right and left, and consists of three pairs of nerves, closely invested with connective tissue, the roots of the second and third *spinal nerves,* and the electrical nerve. Bilharz regarded the last as a new element, inserted between the others, while Fritsch (12) has determined its connection with the so-called lateral nervous system, derived in all fishes from the *trigeminus* and *vagus.* The physiological function of this system is to supply the skin-organ, which is so highly developed in fishes, with secretory and sensory nerve-fibres. The superficial portion of the lateral nervous system of the vagus in *Malapterurus,* as shown by Fritsch, runs over the electrical nerve just beneath the shoulder-girdle, and then posteriorly into the muscles. Comparative observations on the lateral nervous system of the closely allied, non-electrical, common cat-fish (*Silurus*) shows that the *truncus lateralis vagi* emerges after interlacing with the *lateralis trigemini* "in two fasciculi behind the shoulder-girdle. Immediately after its passage it sends a slender branch to the skin for the shoulder region, and a stronger descending branch to the anterior extremities, and their vicinity, and to the skin of the ventral region. A superficial branch is then given off, which passes downwards from the lateral canal in the antero-posterior direction, and sends 5–6 long descending branches to the ventral region just below the skin." *All these branches of the truncus lateralis are wanting in Malapterurus, being replaced* (in Fritsch's opinion) *by the electrical nerve, which here represents a branch of the nerve that in other fishes subserves secretory and sensory functions.*

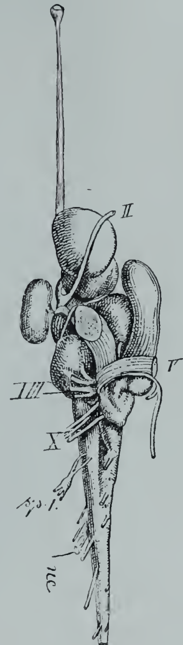


Fig. 262.

And, in fact, like the *lateralis vagi* in the cat-fish, this nerve does, immediately after its exit from the vertebral column, send out a fine ramus to the shoulder region, and pectoral fin, which reappears at the inner border of the head of the lateral muscle to the shoulder-girdle, along with the artery of the electrical organ. It then passes backwards between this and the

straight muscle to the belly, running in the loose connective tissue between muscles and integument, in company with the artery and vein, along the side-line towards the posterior border of the organ. Branches are given off repeatedly on either side,

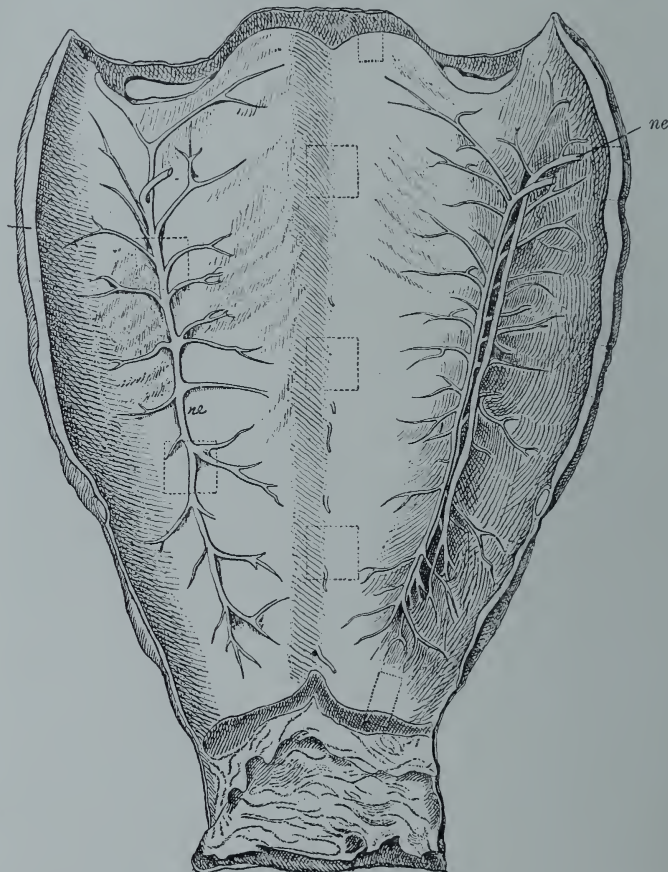


FIG. 263.—Rind of *Malapterurus*, from the inner aspect, showing the two electrical nerves (*ne*), and their immediate ramifications. (Fritsch.)

which, after running a short distance and dividing once or twice, pierce suddenly through the inner tendinous integument of the organ (Fig. 263).

The electrical nerve is of considerable diameter at the middle of its course, this being the more remarkable since—as Bilharz first pointed out—it is a *single, giant, medullated primitive fibre,* which

rises integrally from the spinal medulla, and subsequently bifurcates, by repeated branching, into as many branches and rami as there are nerves in the electrical organ, *i.e.* as are contained within its plates and chambers. The total diameter of the entire nerve, characterised in the fresh state by its peculiar silvery colour, is in no way due to extraordinary size of the original primitive fibre, but much more to the vigorous development of the connective-tissue sheaths, with which the nerve is invested down to its finest terminal ramifications. The disposition of these sheaths is best

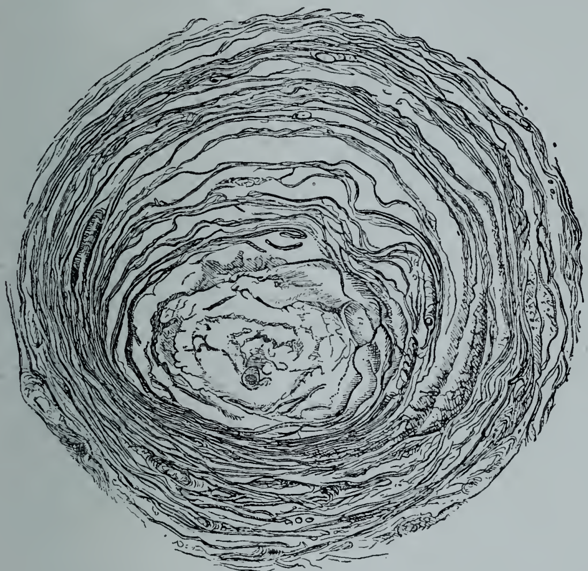


Fig. 264.—Portion of T.S. from electrical nerve-fibre of *Malapterurus*. (Fritsch.)

understood from transverse sections, such as Fig. 264, after Fritsch, from the nerve-trunk. In the centre is the round section of the axis-cylinder, 0·008 mm. in diameter, surrounded with a medullated sheath from about 0·03 to 0·012 mm. in breadth. Externally to this there is first a broad zone of reticulated connective tissue, regarded by Fritsch as the analogue of the Henle-Schwann sheath (the "inner sheath" of Bilharz). This occupies $\frac{1}{10}$ of the total diameter of the trunk, which is about 1·1 mm., and may, with the nerve-fibre, easily be shelled out from the next, concentric layers of connective tissue, which are richly vasculated. Seeing that at every division of a nerve-fibre the total cross-section of

the branches considerably exceeds that of the trunk, the same, of course, occurs in the electrical nerve also, and Fritsch computes that after giving off twenty-five branches only, the diameter of the nerve is more than doubled. Although the cross-section of the axis-cylinder in the medullated terminal branches is of scarcely measurable proportions, the sum of the cross-sections of the collective nervous processes in the plates (which swell enormously after losing

FIG. 265.—*Malapterurus*. One of the two giant ganglion-cells ; *ne*=axis-cylinder process. (Fritsch.)

the medullary sheath) must be reckoned at about 14·113 sq. mm., so that if the superficies of the trunk were only 40·7151 μ the total cross-section might increase (by ramifications and terminal swelling) 346,760 times during its course from centre to organ. This is mainly due to the increase of interfibrillar intermediate-substance, although a fibrillated structure of the axis-cylinder, apart from the stalk of the discs, has not been demonstrated.

A small rounded spot may be detected, even with the unaided eye, upon the long section of the spinal cord, near the origin of

the two electrical nerve-fibres (Bilharz). This spot is distinguished from the surrounding matter of the cord by its darker colour, and is found under the microscope to be a multipolar ganglionic body of giant dimensions, its axis-cylinder process forming an electrical nerve. The two ganglionic bodies (Fig. 265) are lenticular in form, the equatorial diameter being as much as 0·21 mm., the axial about one-half this. Internally there is a large blistered nucleus, which, like the cell itself, is ellipsoid. "The body of the cell is never rounded towards its neighbours, but lengthens gradually into large protoplasmic processes, which subsequently curve distinctly, and form a loose tissue at about the middle diameter of the cell." This becomes more dense after the axis-cylinder process has been given off, and forms a kind of sieve (base of the electrical nerve), from which the nerve emerges, and becomes invested on the other side with the medulla. This structure is the more remarkable since the protoplasmic processes, as well as the axis-cylinder developed from them, are certainly of *nervous* origin.

II. General Action of Discharge from Electrical Fishes

The physiological action of the shock is, of course, of first interest, in so far, at least, as concerns the powerful discharges from the highly differentiated electrical organs of *Torpedo*, *Gymnotus*, and *Malapterurus*. The subjective physiological action of the shock of the fish may, as was pointed out by du Bois-Reymond, take effect under different conditions. It is, however, indispensable (since all action of an animal or vegetable electromotor is produced by short-circuiting) that the curves of current should impinge upon the human body at sufficient density, either directly, or by means of a conductor of resistance parallel with that of the organic tissues, *e.g.* water, moist non-conductors, etc. Metal, employed as the intermediate layer—seeing that its resistance vanishes against that of the moist parts—is a protection against current-diffusion, according to Kirchhoff's law of refraction for electrical currents; so that it is possible—as shown by Humboldt and Gay Lussac—to carry an electrical fish between two movable electrical plates that are in contact, without disturbance from shocks. This fact was compared by the elder Becquerel to the well-known experiment in which the secondary twitch from muscle to nerve (Matteucci's contraction) may be

blocked by the introduction of gold-leaf or tinfoil, between the primary contracting muscle and the nerve of the secondary preparation (cf. I. p. 361).

The effects of shock from *Torpedo* are most apparent when the subject is in circuit with the whole battery (which is vertical in this case), *i.e.* when the lead-off is from upper and under surface of the fish. In *Gymnotus*, too, and in *Malapterurus*, the shock is more powerful in proportion as the contacts are further apart, and the conductivity of the leading-off circuit more perfect, *i.e.* it is strongest when the animal is held in the air by head and tail. Some idea of the force of the electrical discharges from *Gymnotus* is conveyed in the fact that Sachs obtained very marked shocks on grasping an electrical eel 123 cm. long with rubber gloves. On one occasion he received the full effect of the shock. He relates that "he had fallen into the water, and emerged with wet clothes clinging to him, while endeavouring (guarded with the rubber gloves) to throw a lively, fresh-caught eel, over five feet in length, into a trough. The animal escaped and fell on to both his feet, so that its head made contact with one leg, its tail with the other, remaining thus for several seconds. In this position, when Dr. Sachs' legs completed the circuit between the poles of the fish's battery, he received a rapid series of shocks which, since they were not weakened by any deriving circuit, and were easily conducted through the wet clothes, took effect with indescribable intensity. Uttering loud cries of pain he stood as though petrified by the shock, and was quite unable to rid himself of the animal" (du Bois-Reymond, 4 *c*, p. 131).

This was the effect of direct contact with the fish outside the water, but the action is hardly less strong in the case of *immersion in the electrical current*, where the lines of current which traverse the water impinge upon the human body. In this mode of action, to which, as Faraday points out, the electrical organs are peculiarly adapted, each point in contact (or animal body) receives a part of the discharge approximately proportionate to its size. Even the early observations frequently refer to falling under these conditions (du Bois-Reymond, 4 *e*, p. 132). Sachs affirms that horses invariably drop when struck by gymnoti, so that in traversing the caños it is necessary to seek out shallow places, and the foremost rider pushes a stick into the water. "The water becomes filled for a considerable distance with lines of

current from the disturbed eels, and dead fish and frogs then appear at the surface."

As regards the nature of the effect produced by a not immoderately strong discharge, it was remarked by Sachs that it exhibited a strong resemblance to the brief action of the sliding inductorium with so-called vagus electrodes (hook-shaped metal wires). "There is an unmistakable sensation of persistence, of oscillatory character in the shock." In the *Gymnotus* the shock, according to du Bois-Reymond (4 *d*, ii. p. 619) is "less sharp than that from a Leyden jar, and rises more gradually; it is often possible to distinguish several maxima."

"The discharge of *Malapterurus* is surprisingly powerful in comparison with its size. If the head and tail of a vigorous fish are touched in water with the fore-finger, the shock does not indeed reach beyond the middle-finger joint, but if the animal is grasped with well-moistened hands a sharp shock is perceived as far as the elbow. With the secondary coil pushed right up, and a Grove's cell in the primary circuit, a break shock taken through the hand is about equal to a "strong" shock from a fish. Babuchin received such a powerful discharge from one-half of the electrical organ of *Malapterurus*, on exciting the oblongata, that "he remained unconscious for several minutes." He points out the difference in sensation between the shocks of *Torpedo* and of *Malapterurus*. The shocks from the former are, as it were, blunter and duller, those from *Malapterurus* are sharper, more stinging and penetrating; briefly, the difference is the same as that between the currents of the primary and the secondary coils—between the extra-current of the principal, and the break shock of the secondary circuit. Mere contact with the point of a barbel of *Malapterurus* is enough to cause a sharp prick in the finger. This is never the case with *Torpedo*. Du Bois-Reymond suggests that the difference may be due to the different mode of innervation of the organ in the two cases. "At the half of the *Malapterurus* organ (which is innervated by a single ganglion-cell) the shock of the most distant plate is separated from that of the nearer ones only by a minute fraction of a second, as required for the wave of induction to travel the length of the organ. In the organ of *Torpedo*, on the other hand, the duration of the discharge is determined by the time required for the excitation of the entire electrical lobe. And this period, judging by what we know of the transmission of any stimulus

through a ganglionic complex, *e.g.* spinal cord, may be comparatively protracted. It is obvious that the shock will be sharper, more stinging, and more acute, in proportion as the discharge from the plates occurs more simultaneously." The effect, moreover, differs according to the part at which the *Torpedo* shock takes action. Schönlein experienced pain on receiving it on the back of the fingers and hand, while in the palm of the hand it is a mere "pricking" sensation. In artificial excitation with induction currents the feeling of contraction in the muscles of the hand may always be distinguished from the cutaneous sensations. According to Schönlein this never occurs in the shock of *Torpedo;* the discharge must therefore be inadequate to excite the muscles beneath the skin. Faraday compared a medium shock from the electric eel 101·6 cm. long, on which he experimented in 1838, with the discharge of a Leyden battery, charged to the maximum with fifteen jars, and a double-glazed glass surface of 2·258 sq. m. The physiological action of the *Torpedo* discharge is disproportionately weaker, with the exception of the large species (*T. occidentalis*), by the shock of which Captain Atwood was repeatedly thrown to the ground, "as if felled by an axe."

In order more exactly to investigate the action, strength, and direction of the discharge from a fish still in water, Faraday employed a pair of saddle-shaped, curved electrodes (Fig. 266) for *Gymnotus,* invested internally with metallic, externally with insulating substances. These were applied to two points, corresponding with the poles of the organ, of the fish, lying upon an insulating stage (glass plate), which again was gripped by the gutta-percha rim of the saddle. The segments of the fish are then almost as well insulated as if they were in the air. It is best only to leave as much water as just covers the animal when lying upon the glass floor of a shallow trough. In order as perfectly as possible to insulate the part of the body gripped by the saddle in the smaller and weaker *Malapterurus,* du Bois-Reymond made use of a cover for leading off, shaped like the lid of a mummy-case (Fig. 267). This was moulded in gutta-percha to the shape of the animal, the ends being lined with tinfoil (4 *d,* ii. p. 670).

The insulation from the surrounding water was in this instance so complete that even the very delicate method of testing for current escape in water (to be described below) failed to detect any at the time of the discharge. Du Bois-Reymond

(4 *g*, *h*) finally decided on the arrangement shown in Fig. 268, as the most convenient for leading off from the torpedo in water. A circular zinc-plate, covered with flannel, about the same size as the body (v v_1), was placed at the bottom of a glass vessel 30 cm. wide and 10 cm. deep. A portion of the zinc was bent outwards for leading off. The fish lay upon the flannel. The dorsal shield, for leading off from the back, is again a zinc-plate shaped to the fish with the edge turned up; the upper surface is lacquered, and a wooden knob in the middle carries the second wire for leading off.

By this method it is easy to lead off the shock, and to experiment without injuring the animal. A valuable instrument, with many applications, is the nerve-muscle preparation

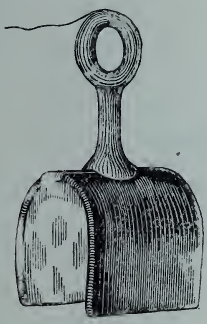


FIG. 266.

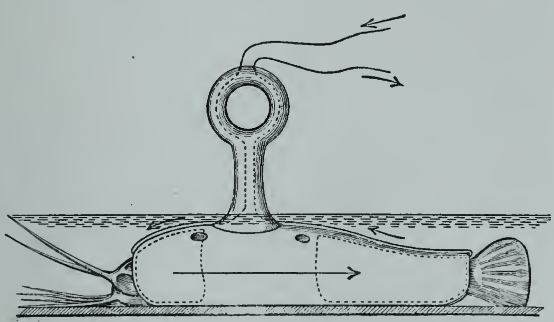


FIG. 267.

of a frog, employed as early as 1797 by Galvani, and later again by Matteucci, in experiments on *Torpedo*. Du Bois-Reymond constructed the so-called "frog-alarum" (Fig. 268, *FW*), by leading off part of the discharge that was passing through the water containing the fish, by means of a pair of submerged electrodes, to the nerve of a rheoscopic leg, the muscle of which rang a bell when it contracted, and thus indicated the successive discharges of the organ. In this way the electrical activity of a fish under water can be observed with little trouble and absolute certainty for hours at a time.

Schönlein (30) has recently employed the telephone for the same purpose, with very good results. He connected one end of it with a lead plate lying on the floor of the fish-trough, while the wire from the other pole ended in a smaller lead plate, that dipped into the water. Even in weak animals (*Torpedo*)

Schönlein found that the discharges were sufficiently vigorous to fill the entire basin, measuring $1 \times 0{\cdot}4 \times 0{\cdot}3$, with lines of current audible in the telephone. He thus detected that the animals sometimes give spontaneous discharges without apparently any direct stimulus, *e.g.* on the approach of other animals, or of the collecting plate. But as a rule a true discharge follows only from

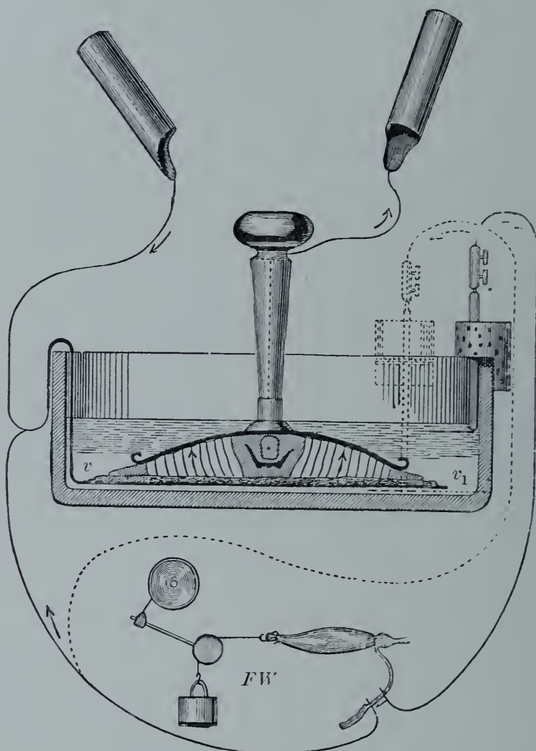


FIG. 268.—Schema for leading off the shock of *Torpedo.* *FW*=frog-alarum. (Du Bois-Reymond.)

contact, or some other excitation. In *Gymnotus*, and according to du Bois-Reymond in *Malapterurus* also, the seat of stimulation is by no means immaterial. The barbels of the last fish seem to be peculiarly insensitive, since their stimulation never produces a discharge. As regards requisite strength of stimulus, again, great differences are apparent. *Gymnotus* at times reacts to the faintest impression, at others a discharge can only be provoked by determined "picking" with a pointed body. In

making preparations from the organ of *Torpedo,* Schönlein usually observed a discharge on cutting through the skin, as well as on removing the cranium, especially if the canals and utriculus were broken into. Division of the medulla oblongata was also accompanied by a discharge.

The relatively considerable duration of all spontaneous or reflex discharges is apparent not merely in subjective sensations, but also objectively with the above modes of investigation. With strong excitation, the hammer of the frog-alarum is continuously pressed against the bell in both *Gymnotus* and *Malapterurus.* When *Malapterurus* is excited, it seldom discharges once only. The bell usually rings 2–3 times, either in quick

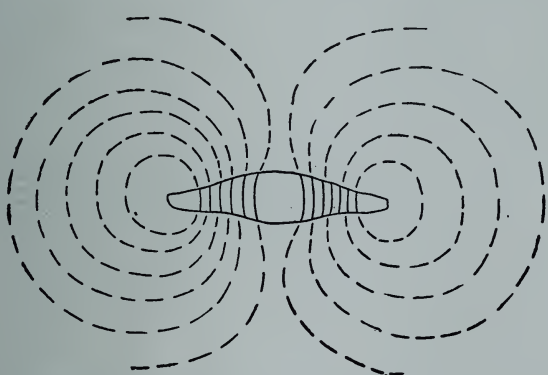


FIG. 269.—Schema of current distribution outside the body of *Torpedo.* (Cavendish.)

succession or at longer intervals. In telephone observations Schönlein found that both pitch and character of sound, from the natural discharge of *Torpedo,* varied considerably. "If the sound were expressed in letters, the vowels *æ, e,* or *i* must be selected, never *o* or *u.*" Brief shocks seem to be best expressed by *R,* sung at different pitches. Longer discharges seem as a rule to correspond with a higher pitch than brief shocks.

The endurance of the fish is considerable. Du Bois-Reymond tested his malapterurus every ten minutes, for two hours. "Including the removal of the fish to the experimental trough and back again, it was excited 11–14 times; it yielded at least twice or three times that number of shocks. During the series of experiments the fish became visibly fatigued. It grew pale, and at last responded only by a single shock when the cover

was put on" (4 *d*, ii. 618). Of *Torpedo*, too, we know that "it keeps up a series of discharges at more than seconds speed, for over a minute." Schönlein states that the living organ, with intact circulation, cannot give more than 1000 shocks, either when the discharges follow spontaneously upon strong protracted stimulation of the animal, or when they are artificially discharged from preparations of the organ. In the first case the animal requires a longer recovery (at least a quarter of an hour) for the restoration of its power of discharge. The excited organ, on the other hand (unlike muscle), shows no recovery after continuous excitation of only 10 sec. with tetanising induction currents. Sachs' gymnotus was electrically non-fatiguable. 200–300 shocks could be elicited from it without perceptible diminution; an animal which had presumably discharged 150 times in an hour could still send a powerful shock through a chain of eight persons, if those at the ends were in contact with its head and tail (du Bois-Reymond, 4 *e*, p. 256).

We have seen that Cavendish (1776) arrived, by means of a submerged model of *Torpedo*, connected with a Leyden jar, at a substantially correct idea of the distribution of potential on the surface, and in the surrounding water—as shown by the accompanying schema, Fig. 269. The improvement in physical technique, more particularly the introduction of the galvanometer, enabled Colladon, and still more du Bois-Reymond, to confirm and enlarge the results of Cavendish in all essential points (4 *g*, *h*, p. 193). Colladon formulated the three following propositions in 1831 *re* distribution of potential upon the surface of a torpedo in air, during discharge:—

1. "All points of the back are positive towards any point of the ventral surface. Intensity of current diminishes in proportion to the distance of these points from the organ; at the tail it is almost at zero.

2. "Two asymmetrical points of the back, or two similar points of the belly, almost always give current through the galvanometer; the point proximal to the organ is positive on the dorsal, negative on the ventral surface.

3. "There is no deflection in the galvanometer from two symmetrical points of the back or belly."

Since the columns, of which the E.M.F. increases with the number of plates, diminish about 0·6 mm. in height from the

medial to the lateral wall of the organ of *Torpedo*, it is quite clear why there should, in the fish in air, be a current as stated by Colladon and Matteucci between median and lateral points, from former to latter on the back, and *vice versa* on the belly. If all the columns were of equal height in both organs, the organs being, moreover, brought together in the median plane, and there united, the centre of the median line would be most positive on the dorsal aspect, most negative on the ventral. "On separating the organs again, the most positive and most negative points in each organ would—as du Bois-Reymond pointed out—

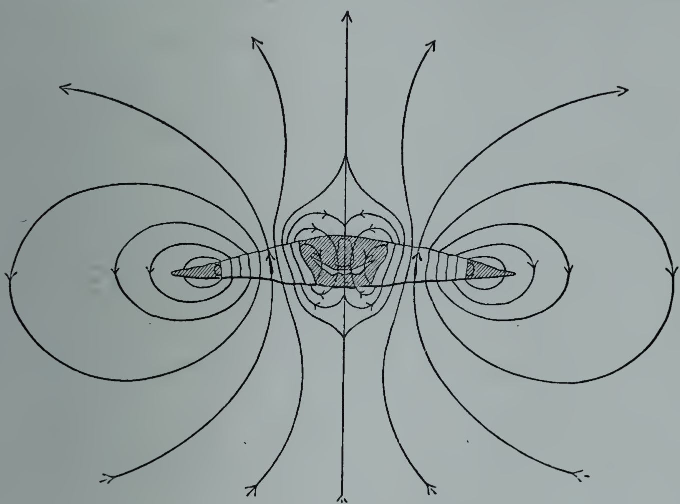


FIG. 270.—Schema of current distribution outside the body of *Torpedo*. (Du Bois-Reymond.)

(in correspondence with the distance between the organs) lie midway between the median edge and the centre." There would thus—at equal height of all the columns—be a P.D. between back and belly in the same direction, although weaker. Reduced height of columns towards the sides, on the contrary, sends the points of greater positivity and negativity to the median border of the organ. There are thus, as du Bois-Reymond pointed out, currents in the back of *Torpedo* from these borders also to the median line, and *vice versa* in the belly. The accompanying Fig. 270 shows the direction of the lines of currents in a diagram of the fish, after du Bois-Reymond. Here we see that the curves "not merely radiate from the so-called polar surfaces, but also cut

the lateral surfaces of the organ. They are directed inwards as well as outwards through the body of the fish, and further fill up the cavity."

With regard to the immunity of *Torpedo* to its own shocks, it is to be noted that "the currents which flow along the back, from the median walls of the organ to the middle line, and conversely on the ventral surface from this line to the border, necessarily find their path through brain and cord; and, since this is the shortest path between the most active parts of the two organs, there can be no stronger current through the torpedo" (du Bois-Reymond).

Du Bois-Reymond was able to reproduce all these effects upon artificial models, by grouping zinc-platinum elements together in series like electrical plates, and dipping them suddenly into water, upon which the current spread itself as in a discharge, and was led off in a similar manner.

On leading off from symmetrical points of the dorsal or ventral surface, du Bois-Reymond obtained deflections from his fish during the shock, which might be due to unequal innervation of the two organs.

In *Malapterurus* du Bois-Reymond established that "during the discharge each point of the organ proximal to the tail is positive to those nearer the head, and that it is unimportant whether the point lies at the circumference of a given cross-section of the fish, or at its back, side, or belly," so that the polar surfaces of the organ lie, as in *Gymnotus*, towards the head and tail.

It follows that the direction of the normal discharge in electrical fishes is invariably at right angles to the plane of the plates. In *Torpedo*, where the plates are horizontal, with normal position of the animal, the discharge therefore occurs between back and belly; in *Gymnotus*, on the contrary, where the plates are, as a rule, vertical to the long axis of the organ, *i.e.* in the transverse plane of the animal, the discharge passes longitudinally from head to tail. The same is the case in *Malapterurus*, where the plates exhibit a similar arrangement.

A very remarkable rule at first appeared to be indicated in the fact, as pointed out by Pacini, that the distribution of the nerves in *Torpedo* and *Gymnotus* occurs always upon that surface of the plate which is negative in the discharge, *i.e.* the lower surface in *Torpedo*, the posterior surface in *Gymnotus*. In this last animal Faraday

had already proved by potassium-iodide electrolysis that "every point of the fish in water, or of its immediate vicinity, is negative to every point anterior to it on the fish, and positive to every posterior point, the effect being stronger in proportion as the points with which contact is made are farther apart, while it disappears on leading off symmetrically to the sagittal plane." This is intelligible if, at the moment of discharge, the anterior surfaces of all the electrical plates are positive, the posterior negative, as du Bois showed upon a submerged model of prisms made of zinc and platinum elements soldered together (4 *d*, ii. p. 683). The current is accordingly ascending ("positive" in direction) in the columns of the organ, *i.e.* directed from tail to head.

Bilharz, having convinced himself that the nerve entered by the posterior surface of each plate in *Malapterurus*, also concluded forthwith that the direction of discharge would correspond with that of *Gymnotus*, without actually being able to perform the experiment. Du Bois-Reymond showed, on the contrary, that the discharge in the *Malapterurus* organ is invariably directed from head to tail, *i.e.* the opposite of Pacini's rule. This is also true of *Raja*.

It was stated at the beginning of the chapter that Faraday had succeeded in demonstrating all the signs of a true electrical discharge (as laid down by him) with one exception, in the shock of electrical fishes (*Gymnotus*). He obtained physiological action, deflection of magnetic needle, magnetisation, production of heat, spark, electrolysis, attraction and repulsion; conduction through hot air (flame) alone seemed impossible, a fact already observed by Cavendish, and of which he had failed to find any explanation. Du Bois-Reymond subsequently pointed out that this is only a special instance of the general fact that, notwithstanding the frequently enormous power of the discharge from electrical fishes, it is unable to overcome even slight hindrances to its passage. This is expressed *inter alia* in the fact that it is seldom possible in *Torpedo* and *Malapterurus* to elicit so-called discharging and closing sparks from the shock; while, on the other hand, it is easy to get separation sparks. In the first case there is a gap between the stationary or approximating metal points, which the current bridges over at closure; in the second case a circuit in which current is flowing is interrupted. Du Bois-Reymond

when experimenting on *Malapterurus*, employed a spark micrometer, with which two platinum points could be brought as close together as 0·01 mm.; he also made slits in strips of tinfoil, which were not wider than 0·0033–0·0050 mm. Yet he never succeeded in getting a discharging spark during his investigations with the microscope in a dark room, although an induced current, imperceptible to the tongue, leapt over the same gap with production of sparks, at 90 mm. distance of secondary coil.

On the other hand, Santi-Linari and Matteucci on *Torpedo*, Faraday on *Gymnotus*, and du Bois-Reymond on *Malapterurus* saw separation sparks, when the fish was stimulated by the contact of mercury with a platinum point, or by rubbing two files together, or by drawing a spring along a cogged wheel. By means of the frog-interrupter it was possible to open the circuit each time by the twitch of the muscle at the acme of the discharge, when the separation spark always appeared. Discharging sparks have been several times observed on *Gymnotus* only. As early as 1773, Hugh Williamson, in Philadelphia, received a shock through a gap in the circuit, the diameter of which he compared to the thickness of "double post paper"; but he saw no spark. Walsh, on the other hand (as communicated by du Bois-Reymond, 4 *e*, p. 158), succeeded in discharging a spark at a slit in tinfoil with a gymnotus brought to London from Guiana in 1775, so infallibly that he was able to demonstrate it 10–12 times in succession to more than forty members of the Royal Society. Sachs again failed conspicuously to produce closing (discharging) sparks in a tinfoil gap of 0·1 mm. Under these conditions it is not to be wondered at that the shock from *Gymnotus* fails to pass through rarefied air and to light up a Geissler tube.

The explanation of all these facts, which are at first sight so remarkable, is simply, as du Bois-Reymond (*l.c.* p. 161) showed, that the current of electrical fishes, like all other animal electromotivity, is due solely to *derivation*. "In the case of two equal currents *A* and *B*, flowing in two conductors of equal resistance, *A*, however, being in an undivided circuit, while *B* is completed by derivation, the addition of an equal resistance to both conductors will diminish *B* more than *A*, the more so in proportion as the resistance of the rest of the circuit is greater."

"If the fish is connected with a metallic circuit forming a

good conductor, an intense current is developed in this, and by opening the circuit at the appropriate moment, a gap is produced at the instant of opening, which is smaller than can be attained by placing two fixed metals in close proximity. Across such a gap, the current, augmented by induction effects, will readily pass as a spark.

"If, on the other hand, there is a previous gap in the experimental circuit, no matter how small, there will be no deriving branch of current in the circuit, capable of sparking across it. It is thus a delusion to suppose that the powerful discharge of the electrical fish is incapable of bridging over the gap, for in reality the gap prevents the development of the derived current, which results in a powerful shock when well conducted. The powerful shock that is expected to spark across the gap is actually non-existent when the gap is present" (within certain limits of extension for the gap).

Accordingly, in all experiments on electrical fishes where strength of effort is required, it is a rule to reduce the external resistance in the leading-off circuit as much as possible. Du Bois-Reymond first pointed out the adaptation of the different electrical organs to the media in which they have to act. "The organs of *Torpedo* require no great internal resistance in sea-water, and can do with less E.M.F.; they are short, with a wide cross-section. The fresh-water organs of *Malapterurus* and *Gymnotus* require great internal resistance, *ergo* greater E.M.F.; these are long with a small section."

Du Bois-Reymond first drew attention to the ease with which a discharging spark can be elicited by the shock from a fish, with the help of induction, by leading it through the primary coil of a Ruhmkorff's inductorium. If a spark-micrometer is introduced into the secondary circuit, two sparks will regularly appear, one larger immediately followed by a smaller. Armand Moreau (du Bois-Reymond, 4 *d*, p. 628) even succeeded in showing the electroscopic attraction and repulsion by the shock, on replacing the platinum points of the spark-micrometer by two bent copper wires, to the ends of which two gold leaves were attached. "At a distance of 3 mm. the movement of the leaves at the moment of the discharge was doubtful, at 2 mm. they obviously attracted each other, and at a less distance they flew together, with a magnificent green flash, which left the leaves in cohesion."

Electrolysis of potassium iodide was often used instead of the multiplier to determine the direction of shock in the fish and the distribution of surface-tension. The discharge was then led in by two annealed platinum points to a strip of filter-paper saturated with solution of potassium iodide. Du Bois-Reymond (4 *c*, p. 163 and 7) then encountered the paradoxical phenomenon that in the discharge from both *Malapterurus* and, as he found later, *Torpedo*, an iodine spot appeared *under both electrodes*, but was as a rule more distinct in the former beneath the point corresponding with the tail. John Davy and Matteucci had not remarked this effect on *Torpedo*, nor Faraday, Schönlein, and others on *Gymnotus*, and Sachs also failed to obtain it in the latter.

Since the alternation of the discharge thus seemed possible, a closer examination was required. It then appeared that the "secondary" iodine spot under the negative electrode can be produced by single induction-shocks also, if, as is usually the case, the circuit is left closed after the current has ceased to flow. Here it is undoubtedly due to the "current from the opposite discharges received by the platinum points dipping into the iodide of potassium solution, under the action of the induction current." "The process in the fish is quite similar to that in the induction circuit. The circuit remains closed for some moments after the shock has been given, however quickly the saddle be lifted out of the water, there being, moreover, no especial reason for haste. During this time a secondary current must cross the current of the fish in the opposite direction. This is derived not merely from the charges of the platinum points which dip into the iodide of potassium solution, but from those of the platinum saddle also. This secondary current must inevitably produce a corresponding spot of iodine under the previous kathode and present anode" (4 *d*, p. 651 f.). Du Bois-Reymond proved by experiment that demonstrable polarisation of the electrodes does occur from the discharge of the fish. The current from the shock was conveniently kept away from the galvanometer (by the frog-interrupter) through a derivation circuit, and in order to make the polarisation visible, it was only necessary to open this as soon as possible after the shock.

The electrical manifestations in those species which were termed above "pseudo-electric" (*Raja*, *Mormyrus*) are much less conspicuous than in the electrical fishes proper, as described

above. Here, as in muscle, galvanometric evidence alone is reliable. James Stark (cf. 32) was led to the discovery of the electrical organ of the ray on hearing a fisherman say that a shock resulted from touching the tail of the living animal. It is, in fact, easy with the galvanometer to determine the fairly energetic action of the organ. If a living ray is stretched, with its ventral side downwards, upon a board (shaped like a draw-net), the body being then immersed in sea-water, so that only the tail projects beyond the handles of the board, it is easy to apply two unpolarisable electrodes corresponding with the ends of the organ. During rest there is, as a rule, little or no difference of potential. Mechanical stimulation of the skin, on the other hand, always produces a discharge of such intensity that even a small fraction ($\frac{1}{100}$) of the current is sufficient to drive the scale out of the field (Burdon-Sanderson and Gotch, 13 *c*). In the leading-off circuit the current passes from posterior to anterior electrode in the organ itself, therefore it is antero-posterior. In the *Mormyridæ*, as pointed out by Fritsch (12 *i*), the electrical current flows in the body from tail to head, *i.e.* in the same direction as in *Torpedo* and *Gymnotus*. Specimens 15 and 20 cm. long produce, as Babuchin remarks, "hardly perceptible twitches in the rheoscopic frog's leg, while fish of 40 and 50 cm. evoke sharp, maximal twitches, and can be felt by man, although not more distinct than from a torpedo 10 cm. in length." In vigorous and selected animals Fritsch was able to detect discharges with the frog-alarum, when the electrodes, dipping into the water of the holder, were brought as near as 20–30 cm. without actually touching it.

A. v. Humboldt had already pointed to the possibility of a *partial* discharge of the electrical organ: he noted that only one of two metal rods at 10–12 mm. distance from the gymnotus received the shock; the other not. C. Sachs placed four toads' legs on four different points of a gymnotus taken from the water. All four twitched with strong discharges, but if weak shocks were provoked by picking at the skin of the tail, the hindmost preparation alone contracted. In view of the innervation of the organ of *Gymnotus*, its "local discharges" (du Bois-Reymond) are easily interpreted, while it seems equally clear that the *Malapterurus* organ can only function as a whole. C. Sachs found a striking difference in regard to the strength

of the discharge from the anterior and posterior half of *Gymnotus*, in the same sense as that previously noted by du Bois-Reymond in *Malapterurus* (4 *d*, p. 630), where the anterior half gave much stronger deflections of the galvanometer than the posterior (in the ratio of about 11 : 6). Since this difference, as shown by du Bois-Reymond, disappears with increasing resistance of the experimental circuit, there is no reason, in *Malapterurus* at any rate, to assume a different E.M.F. in the two halves. The diminishing diameter of the fish (or of the organ) in the antero-posterior direction, with the consequent diminution of resistance in the same direction, sufficiently explains the reaction. In *Gymnotus* there is the further possibility that the posterior prisms of Sachs' bundles (with wide compartments) may give a different electromotive reaction from those with small chambers.

Under all circumstances the shock increases here with the length of the fish, and the question then presents itself whether this is due to diminution of resistance, or to increase of E.M.F., or both. As appears from comparison of the length and weight in different animals, *Gymnotus* grows more in length than in diameter, so that its cross-sections are relatively smaller in proportion as their length increases; and since we may assume that the reaction of the electrical organ will be the same, its resistance also will diminish more slowly than if the organs remained parallel in their growth, or it may even be augmented. In any case the greater intensity of shock in longer fishes must be referred to *increase of E.M.F.*, and not to diminution of resistance (du Bois-Reymond).

The anatomical relations of innervation in the electrical organs of the several electrical fishes show considerable differences as regards the initiation of spontaneous (voluntary) and reflex discharges. In *Torpedo* it might be predicated that the discharge after destruction of the electrical lobe or sensory nerves leading to it could only occur from excitation of the electrical nerves, or of the electric lobe itself. In *Malapterurus*, too, the property of spontaneous and reflex discharges must be associated with the integrity of the two giant ganglion-cells. In *Gymnotus*, on the other hand, the innervation of the organ is evidently more analogous to the muscular innervation of the fish. Humboldt found no shock from the decapitated gymnotus, so that when an animal

was bisected, the *anterior* half alone twitched, and the experiments of Sachs confirm this. He also, in individual cases, obtained "powerful reflex discharges" from the headless trunk, which can be sensibly felt, as well as expressing themselves by marked deflections on the galvanometer. He explains the absence of effect in the majority of cases as follows: "Smaller and smaller sections of the organ are thrown into simultaneous activity by the reflex, just as, on decapitating the common eel, localised excitation of the skin is followed by more local contractions of the muscles." A more exact investigation of these partial discharges, by means of a superposed frog's leg, is very desirable.

The effect of strychnine poisoning, on the other hand (the action of which was proved by Matteucci and Boll on the torpedo), is highly characteristic, and corresponds with what might be expected. Marey, too, employed strychnine to produce reflex discharges easily and certainly upon *Torpedo*, and he made graphic records of the time-distribution of electrical strychnine-tetanus. In order to poison the animal, he dissolved the poison in the sea-water of its trough. Sachs observed convulsive spasms in *Gymnotus* after the injection of strychnine, accompanied by repeated single discharges. Reflex excitability was much exaggerated. "The slightest tap on the wall of the thick wooden trough produced reflex twitches and discharge."

III. Discharge from Artificial Excitation of the Electrical Nerves and Central Organs

Anatomical considerations at once make it clear that *Gymnotus*, *Raja*, and *Mormyrus* are, among the electrical fishes, the least suitable for indirect excitation of the organ, since the anatomical arrangement of the very short electrical nerves presents great difficulties to the dissection of a nerve-organ preparation. "In *Malapterurus*, a cut which hardly draws a drop of blood will expose a long tract of both the nerves, as if prepared by nature. Regular strips may be cut out of the organ with scissors, of any length and breadth, and these, bounded externally by skin, internally by fascia, preserve their form well." In *Torpedo* also, though with more difficulty, it is possible to prepare and excite the four nerves that run from brain to organ. In *Gymnotus*, on the other hand, about 250 nerves enter the elec-

trical organ on either side of the spinal cord. "These are too short to admit of a number of them being collected into a bundle, while each governs too small a part of the organ to be sufficient in itself" (du Bois-Reymond, 4 *e*, p. 187).

In order to make the necessary preparations from *Torpedo*, with simultaneous control of the activities of the organ, Schönlein (30) placed the animal upon a flat dish of zinc, and covered the skin of the back above the organ with a second zinc plate of the same shape; a telephone in circuit with the two contacts signalled the discharges. After dividing the medulla oblongata, and extirpating the spinal cord, there is no difficulty in exposing the electrical nerves. Preparations consisting of the two organs and their corresponding nerves alone are somewhat more difficult.

We have already discussed the character of the pitch, and intensity of the natural discharge of *Torpedo* as observed in the telephone. It is essentially characterised, not merely to touch but also to the ear, by the same manifestations as a rapid series of induction currents, so that with electrical stimulation of the animal it is not always easy to separate the discharging and invariably audible currents from the shocks discharged. This, however, becomes possible, owing to a striking difference in pitch, if with uniform distance of coil the electrodes are placed first upon one of the electrical nerves, and then upon the exposed lobe. In the latter case the tone swells suddenly to "the pitch of a trumpet blast." With weaker stimulation, and the introduction of the acoustic current-interrupter, it is often possible to hear a tone of the same pitch, but different intensity. The pitch may vary with repeated stimulation, and indeed during stimulation, in constant oscillations. Electrical excitation of the part of the brain anterior to the lobe again as a rule provokes a shock, corresponding in intensity with that of the spontaneous discharges, *i.e.* not as a rule coinciding with the stimulation frequency. As was pointed out by F. Röhmann (29), there seems in the electrical lobe of *Torpedo* to be, as it were, a kind of localisation, *i.e.* a definite grouping and arrangement of ganglion-cells, since only a limited portion of the organ can be excited from any given point of the lobe.

It is characteristic of every spontaneous (voluntary) or reflex discharge of an electrical organ, that it is *discontinuous* like voluntary muscular contraction, and consists of a closely-packed series of short impacts of current (Marey's "*flux électrique*"), each

of which corresponds to an elementary motor impulse, producing tetanic contraction of the muscle. Du Bois-Reymond proposes to call each such elementary shock a "partial discharge" ("*Theil-entladung*"), not to be confounded with the earlier local ("*Strecken-*") discharges of the organ. The rate of the incomplete discharges, which—as Marey showed with the Marcel-Desprez signal, as also with the capillary electrometer and telephone—make up a shock, depends much upon the greater or less energy with which the animal reacts, and it falls with increasing fatigue or cooling. There are usually some 25 shocks at a rate of 100–200, on an average 150 per sec. This gives a duration of the total discharge of $\frac{24}{150} + 0{\cdot}07'' = 0{\cdot}23$ sec., assuming for the duration of an incomplete discharge the figure cited by Marey for the shock from the organ produced by a single impulse from the nerve, *i.e.* $\frac{1}{14}'' = 0{\cdot}07''$.

The buzzing sensation often noted in the shock of electrical fishes is not, in the opinion of du Bois-Reymond, to be referred to the tetanic character of the discharge, since the partial discharges follow too quickly, and a total discharge is too soon over. He rather holds "this sensation to be due to a succession of total discharges, which may become half fused, so as to form maxima and minima of the curve uniting the maxima of the incomplete discharges: hence there arises a double tetanising ctenoid" (4 *e*, p. 239).

Among artificial stimuli the electrical current is really the only suitable means of studying the indirect excitation of the organ exactly—for the same reasons as in the nerve-muscle preparation. In *mechanical* excitation (pinching, cutting) of the electrical nerve of *Torpedo*, Schönlein (30) heard a "very slight scratching noise" in the telephone, which could only be detected when the room was quiet. Crushing the nerve between two glass plates gave the same result. On the other hand, Babuchin found the electrical nerve of *Malapterurus* to be sensible at all points to mechanical stimulation. "The bisection of the trunk, and also of its branches, with sharp scissors, pressure, stabbing with a thorn or pointed glass needle, never failed in effect." Chemical stimulation (bathing in saturated solutions of sodium or potassium salts) was practically inactive. In electrical excitation, single induction shocks acted, if at all, only at high intensities. Sachs was unable

to detect " any appreciable response " in a nerve-organ preparation of *Gymnotus* with the strongest single induction shocks obtained from a sliding inductorium by means of the thermo-electric battery (4 *e*, p. 192), and he also failed to get response from the make and break of the current of four Groves in either direction. Sachs apparently refers this to a special property of the electrical nerves, and not to the organ, ascribing to the former a " more solid molecular constitution " and " more stable equilibrium " than to the nerves of other animals. Du Bois-Reymond, on the other hand, points with justice to the part played by the electrical plates of the organ, the similarity of conditions under which the electrical excitation of sensory nerves will discharge reflex movements, and an analogous stimulation showing the electrical organs. " Gentle tetanisation of the sensory nerves produces marked reflex twitches of certain groups of muscles from the cord; strong single shocks elicit no response. Strong single shocks sent into the electrical nerves discharge no shock from the organ, while it responds by tetanus to the gentle tetanisation of the electrical nerves. The electrical plates of the organ therefore react to the two forms of excitation of the electrical nerves, as the ganglion-cells of the cord respond to the same kinds of stimulation of the sensory nerves " (4 *e*, p. 272). Eckhardt (11) repeatedly and successfully excited the electrical nerves of *Torpedo* with single induction shocks, as well as with the constant current. In the last instance Schönlein (*l.c.*) again observed a peculiar response of the nerve-organ preparation of *Torpedo*. On leading off from a bit of the organ, with a current of 16 Dan. and 6 Bunsen passing through the nerve, he found, " according to the direction of current at closure or opening of the exciting circuit, or even at both, a single movement of the scale; during closure, there was in addition a permanent deflection," the direction of which appeared to be independent of that of the current. The possibility of current escape seemed excluded, since on cutting through the nerve and laying the ends together again, as well as on ligaturing it, the deflections were entirely abolished. There is no adequate explanation of this effect, which Sachs apparently noted on *Gymnotus* also (4 *e*, p. 189).

After this discussion it is unnecessary to state that the much more effective *tetanising* excitation from the nerve produces, as in

muscle, a *discontinuous* change of state in the organ. That is to say, it causes repeated discharges at the rhythm of the excitation, which summate into a true electrical tetanus, as may be proved each time by the secondary tetanus of a rheoscopic frog's leg lying on the organ, or otherwise brought into the discharging circuit. From observations with galvanometer and telescope Sachs describes the phenomenon of electrical tetanus (at great distance of coil) in the *Gymnotus* organ as follows: "The thread moves slowly upwards in an absolute, positive direction (*i.e.* according to that of the direction of the discharge), pauses there with twitching up-and-down movements, and then falls again after a short time, although not to the zero-point. Sometimes the thread will suddenly rise again from the initial height at which it rests. When tetanus ceases, the thread drops quickly as though released (4 *e*, p. 193). Rapid succession of the single induction currents is essential on tetanising the organ from the nerve, since even the most rapid hand make and break of the current from 4 Groves proves ineffective.

In *Malapterurus* also, according to Babuchin, the tetanisation of the electrical nerves is followed by discontinuous discharges, which last for a longer or shorter time according to the vitality of the organ-preparation. "The shocks can be felt with the fingers, and make the same impression as when the fingers actually touched the inductorium."

The trunk-fibres of the electrical nerves of *Malapterurus* were found by Babuchin to be little sensitive to tetanising currents. This seems partly due to the thick perineurium, since currents that failed to excite the thick fibres of the trunk excited the thinner branches effectively. Schönlein (30), too, on tetanising the nerves to the organ of *Torpedo* with the rheotome (in order to determine the time-distribution of the discharge), found the threshold of stimulation to be very high in comparison with the stimulus required by frog-preparations, and he is inclined to refer this solely to the large size of the electrical nerves. The diameter in large specimens is over 4 mm., and the cross-section is fifty times as great as in an average frog's sciatic. And, in fact, on splitting up the fibres of an electrical nerve "until the bundles were as fine as in the frog's sciatic," Schönlein found that "the distance of coil for minimal stimulation lay within the same range as for the frog," a fact that is of great importance in the question of immunity, which we shall presently discuss.

Seeing the extraordinary wealth of nerves in the electrical organ, and the comparative inefficacy of curare (*infra*), direct excitation, more particularly electrical, does not give safe evidence for the independent excitability of the substance of the electrical plates. At the same time certain results undoubtedly point to such a reaction. Matteucci made some successful experiments with direct mechanical stimulation (pricking, cutting, etc.) upon the excised prisms of *Torpedo*. He then observed twitches in the rheoscopic frog's leg, when its nerve was applied to the preparation. Du Bois-Reymond, it is true, points out that Matteucci seems "always to have hit upon a visible branch of the nerve."

Babuchin (1) elicited "fairly strong shocks" from *Malapterurus*, on cutting the organ, even at parts where the unaided eye failed to discover any fibres of nerve upon the inner surface, and Sachs also succeeded, by striking an organ-preparation placed between unpolarisable electrodes in the galvanometer circuit lightly with the flat part of a ruler, in obtaining frequent deflections, the size of which depended unmistakably upon the strength of the mechanical stimulation. The same occurred on touching the preparation with a hot soldering-iron. The action of chemical stimulants is especially interesting, since it is here that we should expect excitation of the plates, independent of the ingoing nerves that ramify in them. Sachs found on placing a strip of filter-paper upon the skinned lateral surface of the long section of a strip of organ 3–4 cm. in length (of which all the sections were artificial, the lead-off being from the two cross-sections), that the galvanometer magnet was at once deflected in the direction of the discharge when ammonia was dropped on the paper with a pipette. Ammonia is, of course, a strong stimulus to muscle, while it does not appreciably excite the nerve. Moistening of the cross-section, on the other hand, gives no perceptible effect on the same preparation (4 *c*, p. 178), which may be due to the fact that the ammonia here can only penetrate slowly through the transverse partitions, while it easily gets "into the upper and lower spaces opened by longitudinal section in all the compartments that are beneath the wetted part of the filter-paper."

In order to test the action of direct electrical excitation, Sachs led single induction shocks, through unpolarisable electrodes, into a prismatic organ-preparation lying on the pads of du Bois-

Reymond's zinc trough, as in Fig. 271. It is evident that there must under these conditions be current escape into the galvanometer circuit, which must be investigated, and allowed for at the end of the experiment. There is in the first place the not very striking fact that make shocks do not excite the organ-preparation, while break induction currents elicit effective discharges. The electrical organ therefore reacts like most excitable substances. It is further remarkable that (according to Sachs' experiments) break shocks heterodromous to the discharge from the organ excite more strongly than homodromous currents. Schönlein was unable to confirm this for *Torpedo*. Induction shocks passed transversely to the organ appear to have the least effect. A rapid series of induced (alternating) currents (tetanus) gives large deflections in the direction of the discharge, with a distance of coil at which single break shocks, under the most favourable conditions, give little or no effect. This is again the same reaction as on stimulating ganglion- and gland-cells, as well as all sluggishly reacting contractile substances.

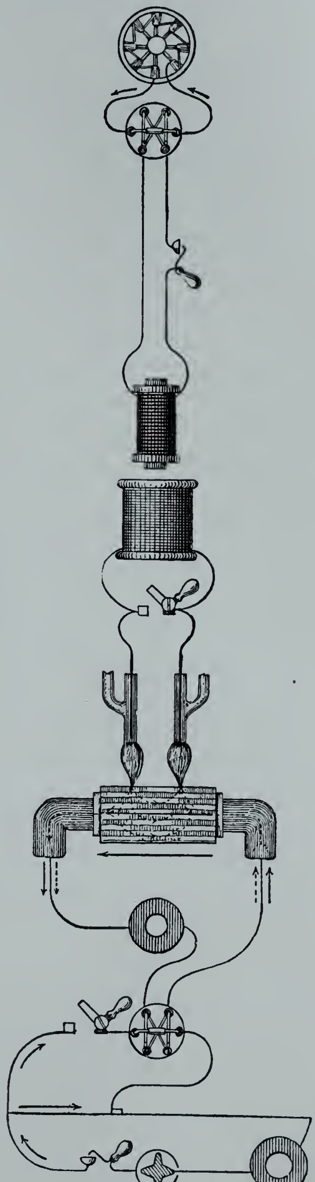


Fig. 271.

The simple method of curarising, by which it is so easy to exclude the nerves in the muscles of most vertebrates, breaks down almost entirely for the electrical organs, since electrical fishes, and more especially *Torpedo*, are, like all other fish, comparatively immune to curare. This is evident in the nerves to the muscles, but still more in the electrical organs

and their nerves, which take much longer in becoming paralysed. With very strong doses of curare, Steiner (33), and later on Ranvier and Boll (4 *c*, p. 194), as previously Marey, succeeded in paralysing not merely the motor but also the electrical nerves in *Torpedo*. The poison, of course, took effect more quickly when injected directly into the blood, than when it was given subcutaneously or through the abdominal cavity. According to Babuchin, 1 cc. of a 2 % solution is sufficient, in the first case, to induce complete motor paralysis in a full-grown torpedo in 15–20 min., while the electrical organ is still reflexly excitable; in subcutaneous application three times the dose was required. *Malapterurus* was found to give the same reaction. Schönlein states that in order to obtain a complete effect, in which case the direct excitability of the organ also disappears completely, it is necessary to give enormous doses (15 cc. of a 4 % solution = 6 decigr. curare), even when the poison is injected directly into the blood (anterior gill artery). Immediately after injection of the first 5 cc., one or two sharp discharges occur with commencement of an opisthotonus, followed by a rapidly-decreasing tetanus of the organ. Weak reflex discharges, however, continue for some time on touching the animal, unless a second and even third injection is given, after which it is still necessary to wait some 20 min. Schönlein inclines to make the slow circulation responsible for this pronounced immunity to curare. Armand Moreau (23) could not discover any action of curare upon the electrical nerves of *Torpedo*. It is easy to paralyse small torpedoes so completely by subcutaneous injections of about ½ cc. of 1 % solution, that there is no sign of movement on stimulating the cord or motor nerves; whereupon mechanical excitation of the skin will still effect reflex discharges of the same strength as before the intoxication.

Sachs made two curare experiments on *Gymnotus*, showing complete paralysis of the electrical nerves with very strong doses. Tetanisation with normal distance of coil then gave hardly any perceptible effect on the galvanometer, while *direct stimulation still called out very marked deflections*, as also the application of ammonia to the long section of the organ-preparation. We cannot, however, regard these observations as proof of the independent excitability of the electrical plates, which Schönlein regards, on the strength of the curare experiment, solely as "nerve-endings."

IV. Time-Distribution of Discharge from Electrical Fishes

Seeing the close relation between most, if not all, electrical organs, and striated muscle, it is interesting to compare the time-distribution of the twitch, or accompanying current of action, with that of the discharge. In the first place it must be asked whether, with a single momentary stimulus, there is any latent period of the elementary discharge which it elicits from the organ. Marey at first decided in the affirmative for *Torpedo*. By means of a pendulum-myograph the circuit (in which there was a rheoscopic frog's leg, as well as the organ which was excited from its nerve by single induction shocks) could be closed for a moment at any given time after the excitation, so that a fraction $= \frac{1}{200}''$ was cut out of the discharge. This fraction, expressed on the leg as a twitch, might therefore be shifted along the discharge, so that on one hand the total duration ($\frac{1}{14}''$), on the other the presence of a perceptible latency, could be determined, since a certain interval between the fraction cut out and the moment of stimulation was required in order to produce contraction. The time occupied by the conduction of excitation from nerve to organ was thought by Marey to be negligible on account of the shortness of the nerve.

Another of Marey's methods was founded on the earlier experiment of v. Helmholtz, by which the fraction of the negative variation of the muscle current that discharges a secondary twitch was determined. Two twitches of a frog's nerve-muscle preparation were graphically recorded, one being discharged directly by an induction shock, the other through the discharge of the organ, generated by the induction current at the same position of the indicator (Fig. 272). The displacement of the curves corresponds with the latent period of the discharge, and less with the time lost in nervous conductivity, which is again neglected, although Marey had already remarked that excitation travels more slowly in electrical than in frogs' nerves, as was subsequently confirmed by Jolyet and Gotch. Gotch determined the commencement of the galvanometer effect on a nerve-organ preparation by stimulating the nerve at points farthest from and nearer to the organ. If the distance amounted to 13 mm. the galvanometer effect began $\frac{2}{1000}''$ earlier on stimulating the

proximal point; this gives a rate of propagation of 6·5 m. per sec. (at 12° C.), or in another case 7·3 m. Schönlein has recently given much higher values (12–27 m.), and reckons them in the same order as those of frogs' nerves.

Marey's experiments seem to give a latent period of 0·01″ for the discharge of *Torpedo*, *i.e.* the value originally given by von Helmholtz for twitch in the frog's muscle. But as here, so in the electrical organ it was subsequently found that if there is any latent period of discharge—in the sense that the causative alterations in the substance of the plates are initiated later than

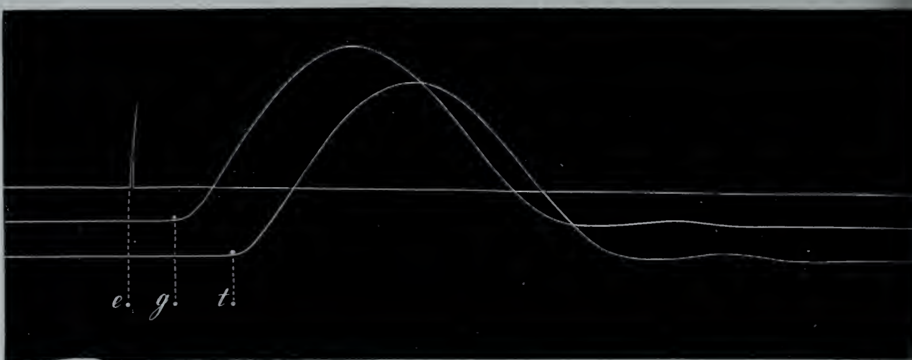


FIG. 272.—e = twitch from the muscle, as marking moment of stimulation; eg = latent period of muscle twitch discharged directly by an induction shock; et = latent period of twitch from the organ discharge; gt = latent period of electrical organ.

the commencement of excitation (which from analogy with the electrical phenomena of muscle is not very probable) — such latency must be much smaller than the original determination.

Sachs, who experimented on *Gymnotus* by a method corresponding on the whole with Marey's, employed *direct* stimulation with opening shocks, because it was found impossible to excite organ-preparations from the nerve by single induction shocks. He also adopted Pouillet's method of time-measurement. The arrangement is according to Fig. 273.

The strip of organ (*VH*) lies between the clay shields of the leading-in electrodes, from which wires lead to the double reverser (*DW*). Other wires come from the unpolarisable electrodes applied to the organ, that lead in the break shock from the secondary coil (*SR*); the latter is discharged by Helmholtz's switch

(WW_1), W_1 being opened at the same moment in which the time-measuring circuit is closed at W. With the double reverser, as in B, the organ-preparation is not excited, and the break shock *directly* excites the nerve of the frog's muscle. The time-measuring cir-

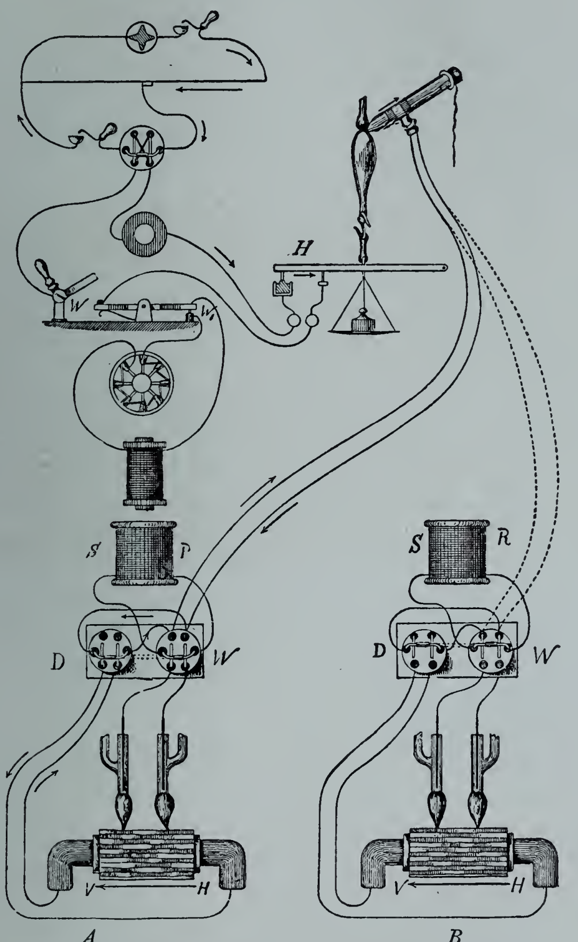


FIG. 273.

cuit is therefore closed only during the period occupied by the transmission and latency of excitation in the nerve and muscle, since the contracting muscle opens the galvanometer circuit at H. In A, on the other hand, the frog-preparation is stimulated by the discharge from the organ-preparation, and the closure of the

galvanometer circuit is accordingly longer than the latent period of the shock. This may be calculated on du Bois-Reymond's formula for the a-periodic magnet $T = \frac{e \cdot t\,m\,a\,x}{F} \cdot x$, F being the deflection from the constant current; e, the basis of the natural logarithms; x, the effect due to current impact; $t\ m\ a\ x$, the duration of this or any other effect under the same conditions.

Sachs accordingly gives a value of 0·00350″, which approximately coincides with the latency of the muscle element as given by Gad. Gotch determines it for *Torpedo* at 5° C., as 0·012″–0·014″; at 20° C., on the other hand, it is only 0·005″. He invariably finds the latent period less in large specimens than in small, and this cannot be altogether referred to the greater intensity of discharge in the first case. Schönlein, on exciting *Torpedo* indirectly with descending constant currents, found, with Bernstein's rheotome, a latent period of only 0·0002–0·00025 secs. Since (as was said above) it cannot be supposed that any appreciable time elapses in a plate of the electrical organ, between the impact of a stimulus and the initiation of the chemical process that underlies the electromotive action, the apparent latency of the discharge in electrical organs must be referred solely to the imperfection of experimental technique.

The *duration of discharge* from the electrical organ seems, like its latency, to be, generally speaking, of the same order of magnitude as that of the muscle twitch. Du Bois-Reymond pointed this out as early as 1857 with the frog-interrupter. He led a branch of the current discharged by *Gymnotus* into the nerve of the frog's gastrocnemius muscle, which in twitching opened the galvanometer circuit. With increased after-loading of the muscle the initial deflections became steadily larger, while if the twitch did away with a shunt to the galvanometer circuit the terminal deflections became smaller and smaller. "With sufficient loading a point is reached at which—in the first case—the deflection of the mirror due to the discharge shows no further increase, while in the second, with unpolarisable (leading-off) saddles, there is only a weak and inconstant remainder of the discharge." Marey subsequently determined the period of the discharge of *Torpedo* (*supra*) with the pendulum-myograph at about $\frac{1}{14}$″. Sachs experimented on *Gymnotus* by du Bois-Reymond's method. His apparatus is given in Fig. 274.

Leading-off saddles are applied to the fish in water, the current

being led through wires to the galvanometer circuit, which includes the frog-interrupter (G_{11}). Two copper electrodes (EE_1) are further placed in the frog-trough, their wires being connected with the muscle (G_1) of the frog-alarum and (G_{11}) of the frog-interrupter. The first was directly excited, owing to the force of the shock from the gymnotus, the last indirectly, from the nerve, by means of the exciting reed. "With the reverser placed as in the figure, the lever of the interrupter forms part of the experimental circuit. The arrows show the direction of current. With the reverser turned over, the lever makes the shunt circuit; this distribution of current corresponds with the dotted arrows."

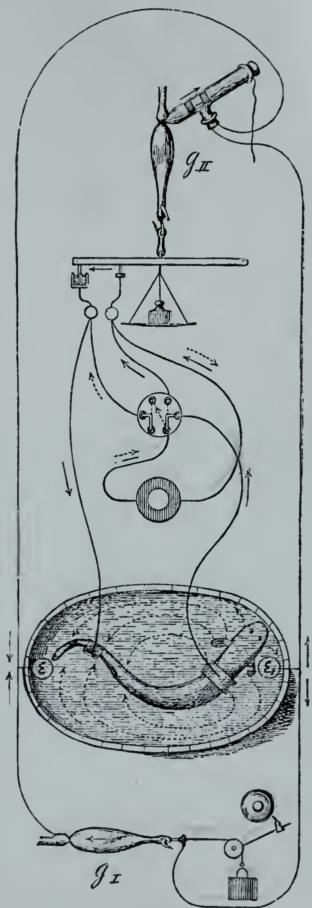


FIG. 274.

Gotch has recently employed another and widely applicable method in his numerous experiments in time-measurement on the torpedo. The apparatus is essentially modelled after du Bois-Reymond's spring-myograph. Three contacts (K_1 K_2 K_3), which are opened in succession by the trigger, were connected as in Fig. 275. K_1 opens the primary circuit of an induction coil, the break shock being passed into the nerve of an organ-preparation. A corresponding part of the discharge that follows acts upon the galvanometer when the opening of K_2 abolishes a shunt to the galvanometer circuit. Lastly, the latter is permanently opened (by K_3), so that the discharge from the organ only acts upon the galvanometer for the period between the opening of K_2 and K_3. The trigger shoots past so rapidly that this interval may be reduced to 0·001″. Hence if K_2 is opened 0·01″ after K_1, while K_3 is gradually withdrawn from K_2, the effect on the galvanometer will be perceptible $\frac{15}{1000}$″ after the stimulation

of the nerve, and reaches its full development at $\frac{22}{1000}''$. For the rest, the rapidity of reaction is obviously modified by temperature.

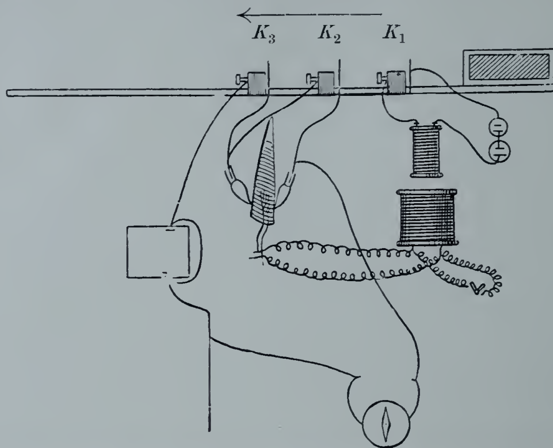


FIG. 275.—Schema of apparatus for determining the duration of the *Torpedo* discharge. (Gotch.)

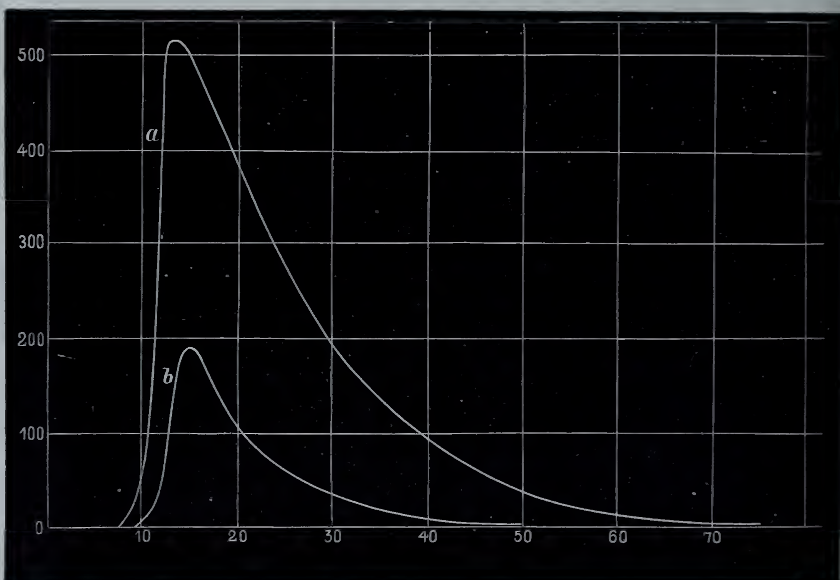


FIG. 276.

Fig. 276 (a schema by Gotch, in which the ordinates are the galvanometer deflections, the figures (10, 20, 30, etc.) on the abscissa $\frac{1}{1000}''$, and their commencement the moment of

stimulation) shows that the discharge from the organ quickly reaches its maximum after the period of latency, which maximum, unlike the latent period, is higher in large vigorous specimens (curve *a*) than in small animals (curve *b*). It declines much more slowly, passing gradually into an after-effect in the direction of the discharge, which may last for minutes after a single brief stimulus. The duration of shock is, in round numbers, 0·04–0·06″ on exciting a lively fish with break induction shocks at room temperature. Schönlein determined the period of discharge at 0·008″ or less, a value that agrees with Gotch's figures for the *direct* total excitation of a bundle of prisms.

Jolyet, in his time-measurements, occasionally observed a rise and fall of the discharge in the organ, on stimulating the nerve with a single induction shock, which he referred to temporal differences in the commencement of discharge in different parts of the organ. Gotch obtained the same effect subjectively on dividing the nerve of an organ-preparation held between the fingers, with a rapid scissors' cut. The oscillatory form of the curve of discharge, with several (even 4) apices, can then be detected unmistakably with the spring rheotome after each single stimulus, both on larger strips of organ, and on bundles of a few prisms only. The following table gives the results of such a series of experiments, and shows that at about $\frac{1}{100}''$ after the first maximum of the discharge there is a second weaker and (after another $\frac{1}{100}''$) even a third still weaker maximum :—

Galvanometer.	K_2—K_3 0·001″ to 0·0125″	K_2—K_3 0·0125″ to 0·015″	K_2—K_3 0·015″ to 0·0175″	K_2—K_3 0·0175″ to 0·02″	K_2—K_3 0·02″ to 0·0225″	K_2—K_3 0·0225″ to 0·025″	K_2—K_3 0·025″ to 0·0275″
$\frac{1}{100}$	0	+48	+367	+316	+75	+120	+225
			I. Max.				II. Max.

Galvanometer.	K_2—K_3 0·0275″ to 0·03″	K_2—K_3 0·03″ t 0·0325″	K_2—K_3 0.0325″ to 0·035″	K_2—K_3 0·035″ to 0·0375″	K_2—K_3 0·0375″ to 0·04″	K_2—K_3 0·04″ to 0·0425″	K_2—K_3 0·0425″ to 0·045″
$\frac{1}{100}$	+212	+89	+64	+98	+130	+30	+24
					III. Max.		

These results are even more apparent from the schema in Fig. 277.

Schönlein noted the same effect in the discharge of *Torpedo* from a single induction-current with Bernstein's rheotome, *i.e.* rise and fall of the climax two or three times in succession. "Usually, but not always, the first apex is higher than the second, and if the latter is greatest the differences of apex height are generally less than in the opposite case. The intermediate section is very deep, often reaching to the abscissa without, however, crossing it on the other side." The duration of the single partial discharges varies little. It is remarkable that the same form of curve with

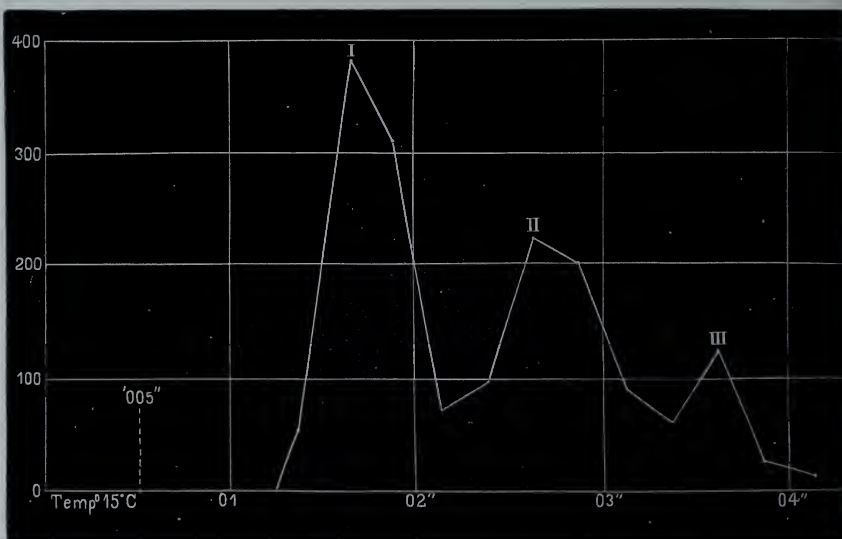


Fig. 277.

several apices is exhibited with similar excitation of the electric lobe, so that it is questionable whether in the last case the ganglion-cells or only the nerve-fibres are excited.

Schönlein obtained true simple curves of discharge with one apex, corresponding with a single, non-oscillating discharge of the *Torpedo* organ, only on stimulating the nerve with single *descending* impacts of current, as shown by the rheotome with 50 Dan. in the exciting circuit. On stimulating with *ascending* constant currents it is seen that the discharge usually begins much later, and increases more slowly, than with the descending direction.

The character of the effects further depends upon the

length of intrapolar tract, and the latent period may, with 40–50 mm., be prolonged 0·0055–0·004 sec. With shorter interpolar tracts there is usually an "introductory apex," its latency of discharge with descending currents being sometimes 0, sometimes, however, of measurable proportions. This Schönlein refers to the diminution, not merely of rate of conductivity, but also of intensity of excitation, due to anelectrotonic inhibition at the anode during each single impact of current (0·001″ duration).

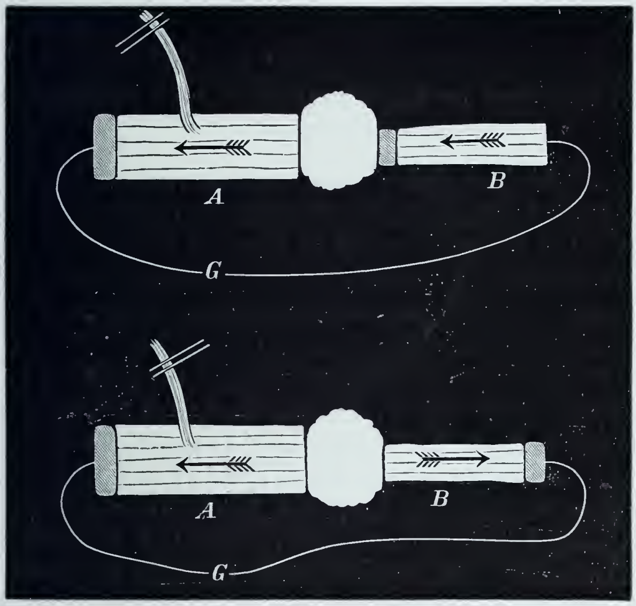


FIG. 278.—Excitation of one organ-preparation by discharge from another, through the nerve. (Gotch.)

We should anticipate that the discharge of an organ-preparation provoked by excitation of the nerve would be sufficient to excite directly a second preparation in the same circuit. The accompanying schemata (Fig. 278) show that there must then be either summation or subtraction of the galvanometer effect. That this is actually the case has been proved by Gotch with the spring-rheotome. The alteration (augmentation or diminution) of the galvanometer effect caused by the discharge of the nerve-organ preparation appears regularly about 0·01″ after the maximum of the discharge. One then asks whether

self-excitation of the organ, by its own discharge, is not merely possible but the rule. Gotch refers the multiple apices of the curve of discharge (*supra*), on stimulating with single induction shocks, principally to a second set of discharges excited from other prisms by the current of those first discharged by the impulse from the nerve, so that the later discharges are in a sense analogous with secondary contraction. Schönlein urges against this view that oscillating discharges might then be expected with brief closures of the battery current, which is not the case.

V. Immunity of Electrical Fishes to their own Discharge

It is in the last degree surprising, in view of the intensity of physiological action in the discharge of electrical fishes, that the most powerful shocks, which at once kill fish or other animals within reach, should apparently not have the smallest effect upon the generators of these electrical batteries, although "the body of an electrical fish is better fitted to receive the shock of its own organs than the body of any other animal" (du Bois-Reymond).

Humboldt made experiments on *Gymnotus* which show the insensibility of the animal to the most powerful shocks from its own kind. He chose out one strong and two very weak gymnoti, placing them so that the weak fish led the discharge from the vigorous animal into his own body. The two weak fish were totally unaffected. He suggested that the skin might be a protection against the electrical current, and this opinion was widely held before the publication of du Bois-Reymond's "preliminary sketch." Du Bois showed first in *Malapterurus* that two wires insulated down to the ends, and introduced into mouth and gut, received the discharge in any position, and led it off externally in accordance with the received theories, thus proving that the shock really passes through the body of the fish, though, strangely enough, the point was again disputed by de Sanctis in 1872. *Malapterurus*, moreover, proves to be as insensible to other electrical shocks as to its own. "The alternating currents of an inductorium, which soon killed the fresh-water fish in the trough, were hardly detected by *Malapterurus*. It only pointed its barbels backwards, and placed itself with its body vertical to the least

density of the lines of current. It occasionally showed disturbance by discharging its own batteries." A dying malapterurus was placed in a small parallelepipedic glass trough, which it nearly filled, and was excited by du Bois-Reymond (4 *d*, ii. 640) with the sliding inductorium, the coils being pushed up, and two Groves in the primary circuit. Its breathing was not disturbed, nor did any discharge follow. It was equally insensible to the constant current from a battery consisting of thirty Groves, which is noteworthy inasmuch as the relative immunity might have been conjecturally referred to the time-distribution of the current (as in smooth muscle). Schönlein further communicated to the author that he was unable in Cephalopoda, Crayfish, and different fishes, with an induction-apparatus double the usual size, having four Bunsen cells in the primary circuit, to excite any sign of action when the wire from one pole (insulated right down to the end) was brought as close as 1 cm. to the animal, the other pole being connected with a small plate on the floor of the holder.

Gymnotus was found by Sachs to be equally immune to its own shocks. He relates that "10 gymnoti were quietly extended in the middle of the canoe, nearly all close together. I dipped my finger in the water at a distance of three feet, and tickled the back of the largest animal with a stick. Several capable persons were told off to watch the animals, one to each. In spite of the distance, I received an appreciable shock. Not one of the animals gave the faintest sign of movement" (4 *d*, p. 267).

At the same time, this immunity (as follows from the previous discussion) is far from absolute. Babuchin saw a small malapterurus that had bitten the flanks of a larger animal draw back to a distance, while he received a shock at the same moment through his immersed fingers, and Steiner, whose observations were confirmed by Fritsch, has seen small torpedoes twitch from shock on coming into contact with larger ones. Schönlein (*l.c.*) states that if pregnant female torpedoes from which the embryos have been removed are laid, still living, upon each other, no *single* animal will move. "They all lie in relaxed condition, or all become suddenly rigid, like a frog from which the spinal medulla has been extirpated. When this last occurs, a shower of electrical shocks passing through the entire heap of animals is plainly felt on the hand. They contract *collectively* without exception." The

fresher and more healthy the animal (*Torpedo*)—the signs being arched back and slight protuberance of the contours of the organs—the more certainly, according to Schönlein, will it react to every discharge.

Since the electrical nerves may be excited by the discharge of the animal itself as well as by artificial currents, the comparative immunity of the electrical fishes might depend principally upon quantitative differences in the threshold of excitation for their nerves as compared with the nerves of other animals, and many facts seem at first sight to support this view. Boll made comparative observations on the nerves of a frog's leg and the first spinal nerves of *Torpedo*, tetanising them with the sliding inductorium according to Rosenthal's method for determining the difference of excitability in nerve and muscle. Contraction always occurred in the frog's muscle at a greater, often far greater, distance of coil than in the *Torpedo* muscles. Humboldt has a corresponding observation. To his surprise he failed to elicit twitches from the exposed muscles and muscle-nerves of *Gymnotus* with a simple circuit (silver-zinc), although he succeeded in doing so under the same circumstances in other animals. Schönlein has recently made legitimate objections to Boll's experiment, protesting against the application, to the doctrine of immunity, of his own experiments on the apparently sluggish excitability of electrical nerves (*supra*). In any case, further comparative observations in this direction are much wanted before any sufficient explanation of the apparently deep-seated immunity of electrical fishes to electrical discharges of any kind can be given. That such really does exist appears to Biedermann evident from the reaction of the most powerful electrical fishes (*Gymnotus* and *Malapterurus*), the shocks of which may be fatal to other animals. Partial attempts at explanation are not wanting. Pflüger suggested that the animals might be thrown at the moment of the discharge of their own nerves, from the central organ, into a state of depressed excitability parallel with anelectrotonus, and thus be steeled against the shock. But, apart from other reasons, it would then be difficult to see why electrical fishes should be "steeled" against the discharges of other individuals, as also against artificial electrical currents. The results of other experiments of du Bois-Reymond and Boll, in proof of the same idea, have been equally negative.

VI. The Supposed "Current of Rest" in the Electrical Organ

The question of whether the electrical organ is normally electromotive during rest, or in the state of excitation only, is obviously of great significance to the theory of its mode of action. This is another aspect of the same problem which—with reference to muscle—formed the subject of the long and animated controversy between du Bois-Reymond and Hermann (*supra*), that ended finally in favour of the latter. If, as has been determined, certain electrical organs are to be regarded as transformed muscles, adapted to a special function, it would seem *a priori* very probable that the discharge of the organ is no more than the "action current" of the "specialised muscle," which would give as little external reaction in the resting state as a true muscle. As a matter of fact, all previous investigations have shown the "rest current" of the electrical organ, when present, to be exceedingly feeble. Du Bois-Reymond himself found the organ of *Malapterurus* totally inactive during rest (4 *d*, ii. pp. 672, 718). "It neither exhibited any similarity with the muscle current, nor did it work, like a battery, in the direction of a discharge." Eckhardt (*l.c.*) gives a precisely similar reaction for the organ of *Torpedo*, in which Zantedeschi and Matteucci had observed weak constant action in the direction of the discharge. These effects, again, were comparatively weak and insignificant. Eckhardt found all points of the dorsal surface permanently positive to all points of the ventral surface, and all points nearer the brain positive in the former, and negative in the latter, to all more distant points. Matteucci measured frogs' gastrocnemii against a bit of organ in the multiplier circuit, proving one to be weaker, two, arranged like a pile, stronger than the organ. He, moreover, observed that the permanent P.D. between dorsal and ventral surface "is temporarily removed after each discharge provoked in the preparation by electrical or mechanical stimulation of the still attached nerve," as could be demonstrated at a low temperature for days afterwards.

C. Sachs, one of whose chief distinctions it was (as du Bois-Reymond said) to have tested the reaction of the resting organ in *Gymnotus*, invariably observed on leading off from the two polar

surfaces—*i.e.* the cross-sections at the head and tail ends of the prisms—a current in the direction of the discharge (du Bois-Reymond's "organ current"), which, however, was again remarkable for its low E.M.F. It usually corresponds with that of a stronger nerve, or weaker muscle (0·15–0·03 Dan.) applied by long and transverse sections, although the strips were about 4 cm. in length and 6–7 sq. cm. diameter. Since there are about 400 chambers in 4 cm. of organ, the organ current of each compartment can only have an E.M.F. of $\frac{0{\cdot}015-0{\cdot}03}{400} = 0{\cdot}0000375-0{\cdot}000075$ Dan. There is also a weak current, in the direction of the discharge, between two points of the natural long section (*i.e.* the natural, lateral boundary of the organ). Du Bois-Reymond, after punching out the electrical lobe in *Torpedo*, either led off from the skin of the dorsal and ventral surfaces of the vertically dependent fish, or with scissors and scalpel prepared four-sided prisms of the organ, containing a fair number of columns, and bordered by a square piece of skin of 5–6 mm. on the dorsal and ventral surfaces. In the first case there is always a current in the direction of the discharge. "It was most pronounced when the highest prisms were at the medial border of the organ between the leading-off parts, and became weaker in proportion as the parts were brought nearer the thinner, lateral edges of the organ" (4 *g*). In the excised pieces there was also a P.D. in the same direction on leading off from two points of the lateral surface of the prism, the magnitude of which increased with the distance of the leading-off points. The deflections were, however, very small in the one case as in the other (between 3 and 23 degrees of the scale); the E.M.F. was also considerably less than that of the nerve current in fish (0·005–0·013 Raoult). For the single plates, du Bois-Reymond estimated a medium E.M.F. of 0·0000117 Dan., *i.e.* three times smaller than that determined for the single plates of *Gymnotus*.

Like Eckhardt (11), Gotch (13) ascribes no great importance to this weak electromotive action during "rest," the more so since he failed to discover it in freshly-caught and perfectly uninjured animals. Upon ten fishes he obtained on leading off from two points corresponding with the centre of an organ, and lying opposite to each other on the skin of back and belly, very weak and fluctuating effects, which occurred six times in the direction

of the discharge, four times in the reverse, and which in his estimation are due solely to inequalities of the skin.

Little as the possible, and even probable, interference of skin currents—the presence of which was demonstrated by du Bois-Reymond in *Torpedo*—can be denied, it must, on the other hand, be admitted that regular differences of potential might, and indeed do, make their appearance under certain conditions (though not in the true physiological state of rest of the organ) even in the wholly uninjured animal. Du Bois-Reymond ascribes these "to the same, though far less active, order of electromotive force as that which produces a discharge *via* the nerve, or with direct excitation." Under these conditions it is an obvious conjecture that the "organ current" may be "an after-effect of the discharge, which passes into it imperceptibly." And du Bois-Reymond elsewhere remarks that the E.M.F. of the organ current may in all probability be regarded as "the remainder of the discharge," while "the fall which always characterises it represents the slow progress of the far quicker but still not quite sudden diminution of the discharge." Finally, du Bois-Reymond explains the negative experiments of Gotch on the organ current of uninjured and resting torpedoes as signifying that the animals "not having discharged for a long time, showed no perceptible after-effect of the last shock, and thus gave no organ current."

By this it is easy to see that the pre-existence of E.M.F. in the resting state of the organ is practically contradicted, and the effects can be altogether explained according to the views of Gotch and Eckhardt.

Since an organ-preparation cannot, of course, be made without stimulating it, it is natural that the E.M.F. of such a preparation should sometimes be considerable. A section through the organ in the vicinity of the electrodes that lead off from back and belly may, as Gotch stated, convert a weak and previously heterodromous current into a somewhat stronger effect, homodromous with the discharge. "Further incisions, that bounded the part led off, so that it only remained in its natural connection on the median side, increased the E.M.F. in the same direction, till it finally amounted to 0·0015 Raoult. If by subsequent transverse sections the resulting wedge-shaped disc of organ was still more reduced, until by sagittal cuts it became a bundle with only a few prisms, the E.M.F. of the

organ will be a little increased after each cut, but falls deeply after a few minutes." Gotch obtained the strongest effect on immersing the mixed bundles of prisms for a short time in hot water, leading off two minutes later from ventral and dorsal surfaces. The E.M.F. (in the direction of the discharge) then rose to 0·0226 or even 0·0336 Raoult, but fell within a quarter of an hour to its normal magnitude. That this was not a case of hydrothermal action follows from the fact that even superficial scalding of the dorsal and ventral halves of the prisms increased the E.M.F. in the direction of the discharge.

On the tail of the ray, Burdon-Sanderson and Gotch (13 *c*) again occasionally determined a "current of rest" in the direction of the discharge, on leading off from the anterior and posterior ends. In organ-preparations this is usually much more developed, especially after the momentary action of high temperatures (immersion in hot water). Every natural or artificial stimulation of the organ causes a more or less pronounced "after-effect" in the direction of the discharge, and this only declines gradually.

After these experiments there can be no doubt that we are here in presence of a slowly-declining excitation of the prisms of the electrical organ (due to mechanical or thermal stimulus), in which the process in each plate may be compared to the gradually disappearing negativity of a strip of muscle modified by veratria, and excited by a brief stimulus. This seems to Biedermann an even more cogent example than that which Gotch selected, of the normal demarcation current in muscle, although both phenomena are fundamentally due to the same cause, the preponderance of the dissimilatory process over simultaneous assimilation. As the persistent excitation in the muscle is expressed by negativity of the affected parts, so in the electrical organ it is expressed by weak electromotive activity in the same direction as that of the strong electromotive action during its natural function. Du Bois-Reymond calls this comparison of Gotch a logical error, but it would not be difficult to invalidate the objections adduced against it. In the present connection, however, this is unnecessary, since we are really dealing only with the question of whether under the above conditions any permanent excitation of the electrical organ in the direction of the discharge can be affirmed or not, and du Bois-Reymond himself admits the former. For how otherwise can the dictum be interpreted that the organ current is only

"an after-effect of the discharge that passes into it imperceptibly," and that it is due to the same, albeit much weaker disposition of electromotive force, as that which provokes discharge *via* the nerve or in direct excitation. Then, however, as was pointed out by Hermann, there remains no more tangible difficulty from the standpoint of his theory (in so far as this can be applied to the electrical organ) than from that of du Bois-Reymond's molecular hypothesis. For the rest it appears to Biedermann that the difference insisted on by du Bois-Reymond between his own and Gotch's view of the organ current is non-existent, since the "persistent excitation" can only be interpreted as the after-effect of a previous effective stimulation.

VII. Secondary Electromotive Phenomena in Electrical Organs

Du Bois-Reymond lays special weight upon the study of that group of electromotive activities which—as they appear in muscle and nerve from the after-effects of artificial currents—were first investigated by him. While their great significance to the theory of current-action cannot be doubted in the case of nerves and muscles, the far more complicated structure of the electrical organs renders them at first sight less appropriate to the experimental determination of further conclusions, if we are to assume, as in nerve and muscle, that every after-effect is a phenomenon, partly of excitation and partly of physical polarisation. If the current passing through any part of the organ has—as we can hardly doubt—a polar action, and this in each individual plate *per se*, and if the connective-tissue walls of partition are the seat of true (negative) polarisation, it is easy to see that the prism-like arrangement of these elements within any given area may, and indeed must, give rise to complex positive and negative effects which would be hard to unravel in any single case.

Du Bois-Reymond thought it remarkable that the electrical organ (of *Malapterurus*) should exhibit "positive polarisation," along with negative after-currents produced by true internal polarisation; the same effect was subsequently interpreted in muscle as the consequence of (opening) excitation. A similar relation with the physiological process of excitation was naturally conjectured to exist in the electrical organ also. Before entering

upon this point it is advisable to cite the essential data *in re* polarisation phenomena.

Let a still-living piece of *Malapterurus* organ, which, as we have seen, is usually isoelectric, be laid across unpolarisable electrodes, serving simultaneously to lead in and lead off; a special contrivance sends in a battery current of definite intensity and duration, and immediately after (when the polarising circuit is opened) closes the galvanometer circuit, as has already been described for muscle. The organ-preparation will then, as a rule, have become temporarily electromotive (polarised), and this—at low current-density—invariably in the direction of a negative after-current heterodromous to the exciting current. This negative polarisation occurs in *Malapterurus in both directions* (homodromous and heterodromous with the discharge) in equal strength, and grows in density and duration, with the product, to still undetermined proportions. *Positive polarisation* invariably occurs first, as in nerve and muscle, at high densities of current, and is most apparent (du Bois-Reymond) with brief currents, its intensity increasing with the duration of the exciting current less rapidly than that of negative polarisation. The greater intensity of positive polarisation in the direction of the discharge (also observed by du Bois-Reymond) is very striking. "The current from head to tail exhibits strong positive polarisation under the same conditions in which that from tail to head gives negative polarisation" (4 *d*, p. 206). Obviously wherever there is simultaneous appearance of both polarisations, the actual after-current is the algebraic sum of the two opposite actions, and it is easy to understand that there might also, under certain conditions, be diphasic (first negative, then positive) deflections, or oscillations of the magnet.

Sachs made analogous observations on strips of *Gymnotus* organ, with the inessential difference that polarisation is, in this case, invariably *negative* at first, while du Bois-Reymond occasionally obtained pure positive effects on the *Malapterurus* organ under certain conditions, which must, however, be referred solely to the lesser density of the currents employed by Sachs. (Du Bois-Reymond sent current from 20–30 Groves through strips of *Malapterurus* that were hardly $\frac{1}{2}$ sq. cm. in diameter.)

Du Bois-Reymond subsequently found occasion in Berlin to

carry on the same experiments on *Torpedo*, without having to stint himself in materials (4 *g-i*).

In order to understand what follows, it must be kept in mind that current in the direction of the discharge is termed *homodromous*, in the opposite direction *heterodromous ;* an after-current opposed to the polarising current is *relatively negative*, its contrary *relatively positive;* an after-current in the direction of the discharge (homodromous) is *absolutely positive*, its converse *absolutely negative.*

Du Bois-Reymond employed prismatic pieces of organ, the polarising current being led in at the end-surfaces covered with skin, while a second pair of unpolarisable electrodes led off the polarisation current, the clay tips being applied to the preparation between the clay shields that led in the polarising current. Here, again, under certain conditions, *i.e.* with brief closure of stronger currents, there may be *positive* polarisation, otherwise a diphasic effect is seen—first a negative, then a positive variation. As in muscle, the positive polarisation is more dependent on vitality, on the normal physiological state of the preparation. "With depressed excitability (*Leistungsfähigkeit*) only negative polarisation at last survives, but it is a long time before the positive effect dies away completely. The relation between polarisation and direction of polarising current is conspicuous." Sachs found in *Gymnotus* that "the negative polarisation current is invariably more marked in the direction of the discharge," and du Bois-Reymond also determined in *Torpedo* that both homodromous (in direction of discharge) and heterodromous currents, after longer closure, or with less excitable preparations, yield (with reference to direction of polarising current) relatively negative polarisation, but that this is invariably stronger with a homodromous current. The apparent contradiction between this discovery and the original observations of du Bois-Reymond, according to which negative polarisation in the organ of *Malapterurus* is independent of direction of current, is explained by the fact that the heterodromous current never produces any relatively positive polarisation either in *Malapterurus* or *Torpedo*. Diphasic polarisation—first relatively negative and then positive—appears with homodromous currents only. If it be admitted that "both currents yield relatively negative polarisation in the same degree, but that the homodromous current is very much stronger than the heterodromous, or alone polarises positively, so that heterodromous, relatively positive polarisation (when pre-

sent) is invariably masked by relatively negative polarisation," the reaction of all three electrical fishes will be found to coincide. The augmentation of relatively negative polarisation, as observed by Sachs and du Bois-Reymond with homodromous currents—as also in du Bois-Reymond's observations on *Gymnotus*—are thus intelligible, since the resulting polarisation current through the galvanometer may assume different values at different stages of any experiment. The accompanying curves (Fig. 279) will

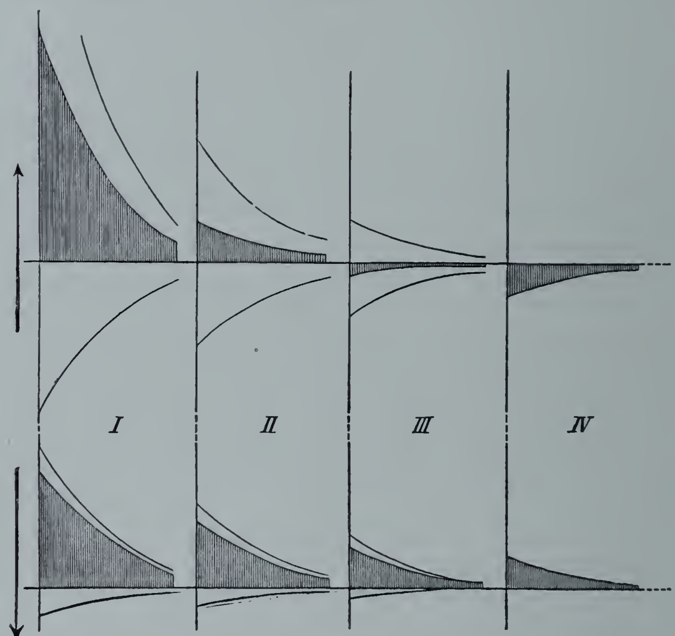


FIG. 279.

elucidate these complicated interference effects of the two simultaneous directions of polarisation, which from obvious reasons cannot be separated as they are in muscle (du Bois-Reymond, 4 *g*, p. 36). Fig. 279 (after du Bois-Reymond) gives a summary of the process in a series of experiments, the two currents being sent alternately through a strip of organ. The abscissæ = time. The ordinates in each cut (i. ii. iii. iv. corresponding with different stages of the experiment) express the moment of closure of the galvanometer after the battery circuit has been opened.

Absolute positive polarisation (in direction of discharge, *i.e.* from ventral to dorsal surface) is drawn above, absolute nega-

tive below, the abscissa. With homodromous currents (upper series, with ascending arrow) the course of the curve above the abscissa is absolutely and relatively positive; below, it is absolutely and relatively negative. With heterodromous currents (lower series and descending arrow) the upper portion of the curve is absolutely positive (relatively negative), the lower portion absolutely negative (relatively positive). The resulting polarisation current through the galvanometer is in each cut represented by the shaded surfaces which comprise the curves resulting from algebraic summation of the two polarisations with the axis of the co-ordinates. It is obvious that the relatively negative polarisation is equal in both currents, while the relatively positive polarisation, on the other hand, is widely different (and with heterodromous currents may fail altogether). Consequently the absolute positive polarisation (which with heterodromous currents is also relatively negative) is unequal in fresh, excitable preparations (i.) at the beginning of the experiment in the two cases. At a subsequent stage this ratio of magnitude may be reversed (ii.); the resulting homodromous polarisation finally becomes absolutely (and relatively) negative, but is always smaller than the relatively negative heterodromous polarisation (iii.); until finally there is *equal*, relatively negative polarisation with both directions of current (iv.). Sachs also saw stage iii. and du Bois-Reymond iv. on *Malapterurus*.

The results of these experiments, as well as of those subsequently undertaken by Gotch (*l.c.*), may be summarised by saying that constant currents, of whatever strength and direction, if led for a considerable time through an organ-preparation, invariably yield relatively negative after-currents which are much stronger with a homodromous than with a heterodromous direction of the polarising current. Stronger homodromous currents, beginning at a certain limen and lasting only a short time, yield strong, absolutely and relatively positive after-currents, that sink very gradually (du Bois-Reymond's positive internal polarisation). Heterodromous currents of equal strength and duration generally yield weaker after-currents, relatively negative, absolutely positive (du Bois-Reymond's internal polarisation).

As the strength of the relatively negative after-currents (negative polarisation), which must be partly caused by *physical* internal polarisation, depends in first degree upon the duration

of closure of the current, we should anticipate that induced currents (which are of such brief duration) would be peculiarly appropriate to the production (with homodromous stimulation) of a positive after-effect in the same direction.

The part played by duration of closure with the constant currents also, is shown by the following table from Gotch :—

Instantaneous closure (7 Groves) homodromous ; galvanometer deflection + 50 (homodromous).
1 second closure (7 Groves) homodromous ; galvanometer deflection − 52 (heterodromous).
Instantaneous closure (7 Groves) homodromous ; galvanometer deflection + 30 (homodromous).
1 second closure (7 Groves) homodromous ; galvanometer deflection − 40 (heterodromous).

By means of a contrivance to be described below, Gotch sent a break induction-shock, first in one and then in the other direction, through an organ-preparation, in a galvanometer circuit which also included the secondary coil and a resistance of 10,000 ohms. On opening the primary circuit, the full after-current in the preparation due to the induced current went through the galvanometer. With a strip of organ 16 mm. long, 7 mm. broad, and 2 mm. in diameter, the deflection (with three Groves in primary circuit and 5 cm. distance of coil) =

Break shock—	heterodromous—	150	(homodromous)
,,	homodromous	650	,,
,,	heterodromous	180	,,
,,	homodromous	780	,,

The excitation effect of the homodromous current is thus much stronger than that in the heterodromous direction. Yet, as Gotch pointed out, this is not invariably the case. At times no difference can be detected in the (exciting) action of the two currents, or the heterodromous current may even be stronger than the homodromous. Gotch is inclined to bring this into relation with the facts observed by Eckhardt, to the effect that descending induction-currents *via* the nerve excite more strongly, since the homodromous current passes through the majority of the finer branches of the nerve in a descending direction. The exceptions are no doubt due to the fact that the larger nerve-trunks sometimes lie in the organ-preparation, so that they are traversed by descending heterodromous currents, and produce an effective excitation.

The galvanic effects of the homodromous current usually increase with the strength of the exciting current, and it can be demonstrated many hours after the preparation has been excised, although it disappears completely after scalding. Here, as in indirect excitation, there is a very slow decline of electromotive effect, lasting for several minutes, its development and time-distribution corresponding throughout with the discharges induced by indirect excitation.

An important fact, as observed by Gotch, is that *partial* longitudinal passage of current in an organ-preparation discharges an excitation effect (after-current) within the part that is traversed only, and not beyond the poles. It follows that *excitation in the longitudinal direction of the prisms is not transmitted from one plate to the next.* Each plate appears to be physiologically insulated from all the rest, and total discharge of a whole prism can only occur either when all the nerves which supply them are excited, or when an electrical current traverses all the compartments in series.

As regards the interpretation of the absolute, and relatively, positive after-effect from homodromous exciting currents, du Bois-Reymond reminds us of two possibilities:

(i.) Like the current of rest in the organ, it may be viewed as the after-effect of a discharge caused by electrical excitation.

(ii.) It may be interpreted on the molecular theory "as the consequence of a prismatic arrangement of the electromotive molecules in direct consequence of the homodromous current."

In reference to the last view, it may be stated that du Bois-Reymond, in order to explain the discharge from the plates, *i.e.* the electromotive action of each single plate of the organ, assumed its construction from dipolar molecules, similar to that said to underlie the electrical manifestations of nerve and muscle. In the resting state the molecules turn their poles either towards all possible, or in two opposite directions, so that the effect disappears externally. In discharging, on the contrary, they "collectively turn their positive poles towards the surface of the organ, whence proceeds the positive current." Du Bois-Reymond pictures the molecules as "a free crowd revolving round their centre of gravity, in the direction of the axis, by a chemical force comparable to some extent with the respiration of the organ." "Several molecules may lie behind one another in the

cross-section of the plate, so that the organs thus form prisms with a much larger number of constituents than follows from the number of the plates."

If in the discharge of the organ we assume a sudden transition of the dipolar molecules from the "peripolar" to the "pile-like" arrangement, the process that takes place obviously coincides with that which du Bois-Reymond postulated in order to explain the (galvanic) electrotonus of medullated nerve.

But if the molecular hypothesis has already been proved inadequate for nerve and muscle (to say nothing of gland-currents and plant-currents), save on the boldest hypotheses to account for the phenomena, we have the more reason to reject it for the electrical organs, since all known reactions of these structures can be explained from the "Alteration Theory" without difficulty, starting only from the fundamental notion that chemical differences are initiated in each plate in consequence of excitation from the nerve, which produces a P.D. between the interfaces in the given direction.

Hence we must fall back upon the view, supported as du Bois-Reymond himself admits (4 *g*, p. 46) by the strongest reasons, *that the absolutely and relatively positive polarisation of the electrical organ by the homodromous current is nothing more than the after-effect of the discharge produced by the latter.*

It therefore becomes very difficult *not* to regard the homodromous positive after-current as the remainder of a previous excitation, even from the standpoint of the molecular hypothesis. Since this explains the discharge "from a pile-like arrangement of the electromotive molecules," it is necessary to ask (as du Bois-Reymond himself pointed out) "in what particulars this arrangement and that produced directly by the homodromous current differ? why the latter does not always complete itself in a discharge?" Du Bois-Reymond imagines that "there may be two states which, although both associated with a pile-like arrangement of the molecules, and identical in their external action, are yet distinct *within the electrical* plate" (since one corresponds with discharge, the other with absolute positive, homodromous polarisation). Yet this seems to present far more difficulties than the conception that,—just as there are at the seat of direct excitation, at the close of a muscle-twitch, prolonged galvanic alterations (negativity), recognisable as the after-effect, or more

properly continuation, of the excitation—so in the electrical organ also the true discharge (shock) may pass off in a homodromous current.

We may admit, with du Bois-Reymond, that "every absolute positive effect is not a *discharge*," just as every excitation of the muscle, even if demonstrable on the galvanometer, does not produce a visible contraction (twitch); in the fresher preparations du Bois-Reymond often observed a very pronounced effect, which drove the scale out of the field of vision, and in which we must undoubtedly admit *the after-effect of a discharge*, if not the last phase of it. "This phenomenon," he continues, "is, however, quite distinct from ordinary absolute positive polarisation (obtained after frequent repetition of the experiment on the same preparation under identical circumstances), since it exhibits no duration proportional with the original intensity." Yet this is just as little the case in the mechanical and galvanic consequences of excitation of the muscle.

If the absolute positive (homodromous) after-current in these experiments is to be viewed as the after-effect of exciting the organ-preparation by the homodromous current, we may expect it to be very marked after brief tetanisation with alternating currents. In order to avoid the disturbances caused by the inequality of time-distribution in the make and break shocks of the ordinary sliding coil, du Bois-Reymond used a Sexton's machine, which produces series of quite congruent alternating currents. The results were uniform; no matter how the ends of the rotating coils were connected up with the dorsal and ventral surfaces of the preparation (*Torpedo*), or what was the duration of the tetanus, there was always an absolute positive after-current, "in fresh preparations of such magnitude that the scale disappeared from the field, the effect becoming gradually weaker."

The striking difference in the relative strength of homodromous and heterodromous exciting currents in the electrical organ, seems to depend intimately upon positive homodromous polarisation, as du Bois-Reymond observed in his earliest polarisation experiments on the *Malapterurus* organ. "The descending homodromous current in *Malapterurus* was always stronger in fresh strips than with the ascending (heterodromous) direction, in the ratio of 100 : 112, 116, even 125. In boiled and in moribund strips the difference vanished." The same fact was

even more apparent later on in preparations of *Torpedo,* in which the homodromous current (of 30 Groves) was more than double as strong as the heterodromous. A similar effect was seen still more plainly on stimulating with induced currents, when the dependence of the seeming irreciprocity of conduction upon current density in the electrical organ was apparent. Du Bois-Reymond "sent opening shocks from the sliding inductorium (the primary coil being filled with rods), from surface to surface of the skin in a preparation of *Torpedo,* which rested between the clay shields of the leading-in vessels. The galvanometer was included in the same circuit." Each shock sent in by opening the mercury key traversed the preparation alternately in the homodromous and heterodromous directions. In the following table RA stands for distance of coil, the figures correspond with the deflections, reduced from 5000 turns at 20 mm. distance from the galvanometer mirror :—

RA= 0	↑501	↓215	↑501	↓215	↑453	↓215	↑477	↓191
RA=10 cm.		↓ 25	↑ 28	↓ 27	↑ 28	↓ 27	↑ 27	
RA=15 cm.			↑ 7	↓ 7	↑ 7	↓ 7		
RA= 0			↑453	↓227				

Above a certain limit of current density the homodromous (↑) current is thus much stronger than the heterodromous (↓).

It should not be unnoticed that, as has been said, "positive polarisation" exhibits the same dependence upon the density of the polarising (homodromous) current. Since it further shows augmentation in proportion with the length of prismatic tract between the leading-off clay points, and therewith the number of polarised plates, the difference in intensity between homodromous and heterodromous current is the more distinct according as the distance between the leading-in electrodes on the lateral surface of the organ-preparation is greater, so that we may say that the apparent irreciprocity of conduction grows, like positive polarisation, with the length of the prismatic tract traversed. In this respect also it has been proved that the ascendency of the homodromous current is much more pronounced with induction shocks, or brief constant currents, than with longer closures. Both manifestations are further associated with vitality, and do not appear with sodden or spontaneously defunct preparations, or with transverse passage

of current. This notwithstanding, du Bois-Reymond refers the difference of current-intensity in the homodromous and heterodromous directions, not to inequality of E.M.F. in either case,—since the relative and absolute positive after-current follows on the homodromous polarising current,—but to a *real* irreciprocity, *i.e.* to unequal resistance in the two directions, the organ conducting better in the direction of the discharge than in the other. It is evident that such a mode of conduction, "which is thus far without any counterpart," can hardly be accepted without stringent justification. When all attempts at deciding the point showed only that, "contrary to all appearance, it is not necessary to invoke irreciprocal resistance to explain the facts," du Bois-Reymond finally believed that he had found such justification in his determinations of the resistance to conductivity in the electrical organ (*Torpedo*). He compared the resistance in prisms of the electrical organ of uniform length and diameter, of frog's muscle (parallel with the fibres), and of salt solution (sea water). With this object the different bodies were enclosed in glass tubes of uniform dimensions, and traversed longitudinally by current. The resistance of the circuit, which included a galvanometer as well as the tubes, was measured by the reciprocal magnitude of the galvanometer deflections, as caused by the opening current of a sliding inductorium. He found that an organ-preparation drawn through the glass tube was a far worse conductor, even with homodromous passage of current in the long directions of the prisms, than frog's muscle parallel with the fibres, or salt water, under the same conditions.

Du Bois-Reymond thence concluded that if the ascendency of homodromous currents depended upon positive polarisation—*i.e.* an additional E.M.F., amounting even to 40 Groves—the organ-preparation would, in comparison with muscle, or with physiological salt solution, conduct better, and its resistance would therefore "seem to be enormously increased," when it loses positive polarisability, along with its vital properties. Neither consequence, however, occurs in du Bois-Reymond's experiments, but rather the contrary. Without referring to this fact, which it is hard to judge without personal investigation, Gotch, with whom Schönlein is now in full agreement, endeavoured by direct experiment to disprove the theory of irreciprocal conduction. He employed apparatus modelled on the "spring myograph," in which the

shooting trigger successively opens three contacts. The first of these (Fig. 280, S_1) opens the circuit of the primary coil of a sliding apparatus, the second, S_2, abolishes the shunt to the galvanometer, which can only then be affected by the current from the organ-preparation; and, finally, the third, S_3, opens the galvanometer circuit again, so that the effect in the galvanometer can only last for the interval between the opening of S_2 and that of S_3. This interval, in Gotch's first experiments, was 0·02 sec. If S_2 is shifted close to S_1, so that the shunt to the galvanometer is opened almost simultaneously with the inducing circuit, the former will exhibit the

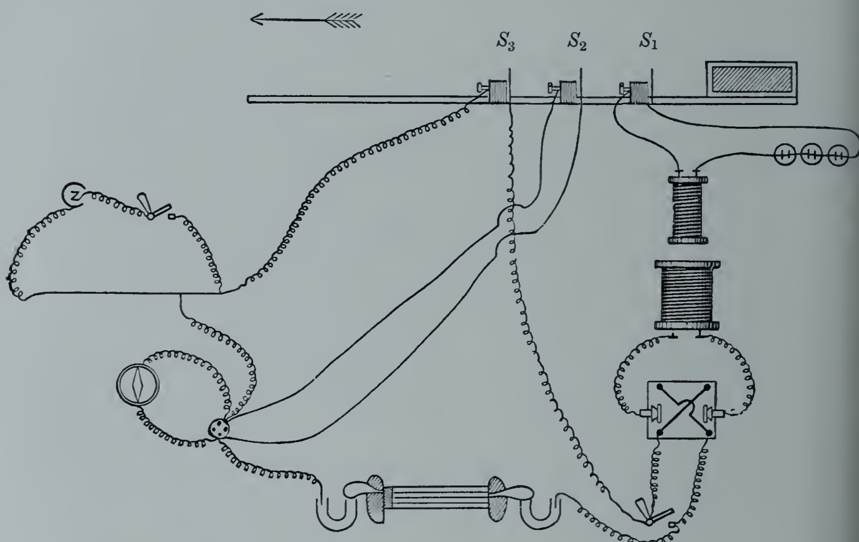


Fig. 280.

same intensity with both homodromous and heterodromous direction. This result can obviously be referred only to the fact that the galvanometer circuit was closed in Gotch's experiments for a very short time after the moment of stimulation, while in du Bois-Reymond's method, not merely the exciting current, but also the whole after-current of the preparation, passes through the galvanometer. In the first case, therefore, the homodromous after-current (positive polarisation, in du Bois-Reymond's sense) can add nothing to the homodromous induction-shock which produces it, since, according to Gotch, it is not developed for 0·05 sec.

Gotch subsequently extended his operations (*l.c.*), making the

interval between closure of galvanometer circuit and moment of stimulation still finer, by means of the same apparatus. He found, in accordance with his previous observations, that when the closure of the galvanometer was shortened so much that the induction-current alone could affect the galvanometer ($S_2 - S_3 = 0'' - 0{\cdot}0025''$) there was no difference in the deflections produced by the homo- and heterodromous currents; at the next moment the electromotive action of the organ-preparation discharged by the shock makes its appearance ($S_2 - S_3 = 0{\cdot}0025'' - 0{\cdot}005''$) as the homodromous after-current, and increases rapidly with further augmentation of closure. The apparent irreciprocal conduction thus arises only when the action upon the galvanometer of the exciting induction-shock is combined with that discharged from the organ-preparation (du Bois-Reymond's positive polarisation).

In further confirmation of this view we have the results of experiments on *the influence of varying temperature upon the consequences of direct excitation of organ-preparations.* Gotch was able to show easily, by means of his spring rheotome, that the intensity, and more particularly the time-distribution of the excitation effects, on applying single homo- and heterodromous induction-currents, are essentially influenced by temperature, and that in the direction we should *a priori* expect in the matter of discharging an excitation. As appears from comparison with the curves in Fig. 281, which give a graphic representation of the experimental results (the ordinates corresponding with the galvanometer deflections, the abscissæ with the interval after the moment of excitation, at *o*), the intrinsically less important effects of excitation in the cooled preparation are considerably retarded, and only become appreciable on the galvanometer long after the induction-current has been made, so that there is a long "latent period" during which the closure of the galvanometer circuit has no effect. It must thus be relatively easy to separate the effect of the induction-current upon the galvanometer from that of the excitation (supposed positive polarisation), and hence to determine whether irreciprocity of conduction really exists or no. Gotch succeeded in demonstrating that apparent irreciprocity does appear at higher temperature (22° C.) with the same closure of the galvanometer, while the same preparation cooled, under otherwise uniform conditions, conducts

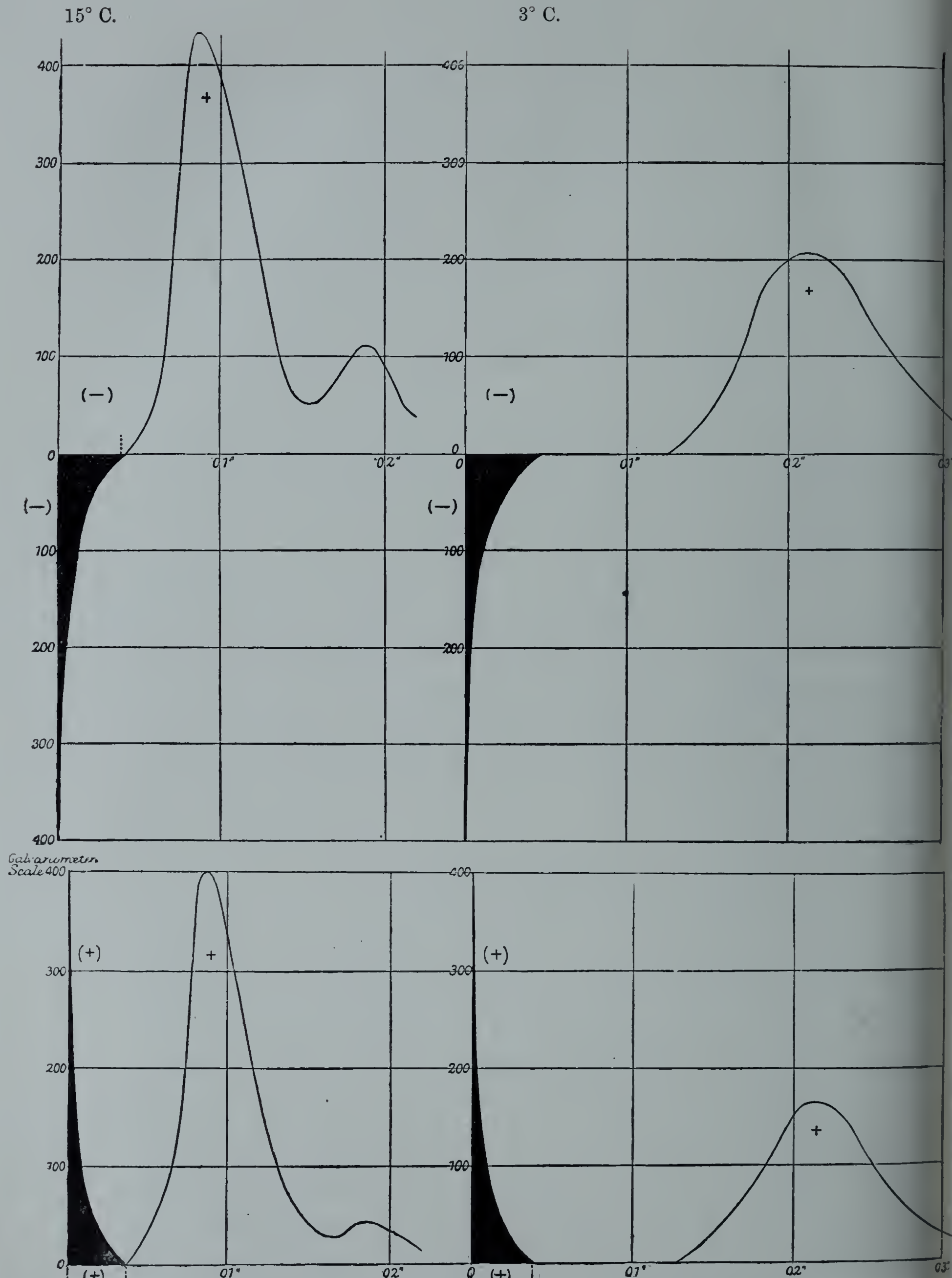


FIG. 281.—Graphic representation of the distribution of the discharge in direct excitation of an organ-preparation (*Torped*), homodromous (+) and heterodromous (−) induction-shocks at 15° and 3° C. The shaded part of the curves corres[…] with the exciting induction-currents. (Gotch.)

the induction-current equally well in both directions, as appears from the following table:—

Temperature.	Direction of Current.	Duration of Closure.	
		$S_2 - S_3$ 0″ – 0·005″	$S_2 - S_3$ 0″ – 0·01″
22° C.	Homodromous	+338	+475
	Heterodromous	−290	− 12
8° C.	Homodromous	+270	+380
	Heterodromous	−270	−174

There is as little reason for assuming irreciprocal conduction in the less differentiated electrical organ of *Raja*. With direct excitation of an excised strip of organ, by single induction-shocks, there will be a single discharge after an interval of about 0·005 sec., the direction of the exciting current being quite immaterial. It is only when the closure of the galvanometer circuit occurs at a time when the discharge of the organ has already taken place that the apparent irreciprocity is again visible in consequence of the algebraic summation between the discharge and the exciting current. When the direction of the induction-current coincides with that of the discharge, the deflection increases with the duration of closure, while in other cases it declines, and is eventually reversed (Gotch, 13 *c*). This is not the place to enter more in detail into du Bois-Reymond's treatment of the teleological significance of " irreciprocal conduction " of the electrical organ.

VIII. Theory of Discharge from Electrical Fishes

Without entering further into the older and in part very naïve views that were briefly alluded to at the beginning of this chapter, and which do not at the present level of knowledge call for serious discussion, we will only consider certain newer theories, *in re* the discharge of electrical fishes, which have indeed been contradicted, but which still claim our interest, because they show how the theories predominating in nerve- and muscle-physiology were adapted to the electrical organ also.

In 1873 Boll discussed the possibility of "explaining the discharge of the electrical organ solely by the negative variation of the nerve current, concomitant with innervation. In this arrangement the dorsal surface of the electrical plate (of *Torpedo*) would at the moment of innervation become positive, the ventral surface negative, as actually occurs." The free ending of the nerve-fibres within the plates suggests the question, "What, under these conditions, must finally become of the negative variation of the nerve current, since it accompanies the excitatory process within the nerve-fibre in every case to the extreme periphery: and whether the more than million-fold multiplication of this variation of the current as engendered in the electrical plates of *Torpedo* (not *Malapterurus*) by the anatomical relations of the nervous ramification may not be a sufficient explanation of the discharge of the *Torpedo?*"

But, as du Bois-Reymond pointed out (4 *e*, p. 276), this hypothesis in the first place predicates the existence of a current of rest, caused by the "natural" cross-sections (acting like artificial sections) of the nerves in the plates, and accordingly heterodromous to that of the discharge. Instead of this permanent current—which must correspond in E.M.F. with the discharge if the nerve current is to disappear in the negative variation—there is only an inessential P.D. during rest, and the resulting "organ current" is always homodromous with the discharge, as the after-effect of which we have learned to characterise it. Du Bois-Reymond declared it to be "no bad hypothesis" which, in order to explain this, assumes "the cross-section of the nerve to be covered over by a parelectronomic layer, the electromotive activity of which does not merely neutralise that of the former, but even to some extent outweighs it, and which has no part in the negative variation. At the moment of the discharge, the E.M.F. of the nerve current disappears in the negative variation, and the discharge is brought about through the release of E.M.F. in the parelectronomic layer."

In the meantime, however, such an assumption became illegitimate, even from the standpoint of the molecular theory, owing to the indubitably powerful E.M.F. of the *Torpedo* discharge,—apart from the fact that Boll's hypothesis does not apply to *Malapterurus*. As we are about to show, there are even in *Torpedo*, not to mention the other more powerful electrical

fishes, considerable magnitudes of E.M.F. which, as du Bois-Reymond himself pointed out, cannot be explained on Boll's hypothesis, owing to the very marked short-circuiting that exists under all circumstances between the individual nerve-endings. In *Malapterurus,* however, where *one* axis-cylinder is alone correlated with each plate, each axis-cylinder would, as du Bois-Reymond remarks, under even the most favourable conditions (such as "that the point of junction should contain a cross-section of the nerve with the parelectronomic layer, and that, as appears hardly possible, this cross-section should be a superficial element at right angles to the direction of activity in the organ), be embedded separately in the mass of the plates, whereby such a diminution of its external action would result, that there could no longer be any question of explaining the discharge of *Malapterurus* by the variation of the electrical nerve-endings. Du Bois-Reymond further points out that on Boll's theory the existence of the electrical plates (often of such a complex structure) would have no significance in the electrical organ, and would be inexplicable.

As we have said, it was du Bois-Reymond who first, in 1843, expressed his conviction that it was the latter (the so-called "gelatinous discs") which "at the moment of discharge become electromotive in a given direction, under the influence of a nervous agency stimulated by whatever means," and which multiply their action after the manner of the voltaic pile. It would thus not be the negative variation of the nerve current that produced the discharge, but a process in the electrical plates transformed from muscles, *comparable with the negative variation of the muscle current,* as set forth from the standpoint of the pre-existence theory. Du Bois-Reymond (*supra*) would accordingly represent each plate as containing countless dipolar electromotive molecules, "able during rest to turn their poles either in all possible or in two opposite directions, so that the external action neutralises itself, while during discharge the poles are turned rapidly and collectively toward the surface of the organ, whence proceeds the positive current." Du Bois-Reymond reckons as one of the main supports of this theory the dictum derived from Delle Chiaje's and Babuchin's doctrine of the preformation of the electrical elements, that *the E.M.F. of the discharge must increase proportionately with the diameter of the plates.* Since the E.M.F.

increases with the size of the fish (whether *proportionately* remains, as Hermann pointed out, 14, p. 486, an open question), while the number of the prisms (or plates) is unaltered, a direct relation between the diameter of the plates (*i.e.* number of molecular layers in du Bois-Reymond's sense) and the E.M.F. may be assumed as proven, although Schönlein disputes this on the ground of his experiments (30, p. 503). This, moreover, coincides with the small diameter of the plates of the *Torpedo* organ 9·6 μ, as compared with those of *Gymnotus* 8·2 μ, and *Malapterurus* 4·8 μ. As stated above, the *Torpedo* organ, adapted to sea-water, can suffice with less E.M.F., while those of the two fresh-water fishes require much greater E.M.F. to meet their higher internal resistance (greater length, smaller cross-section). Given the surface mass, and under the presumption that the E.M.F. of the plates is proportional to their diameter, du Bois-Reymond (4 *e*, p. 286) finds the ratio of E.M.F. in the entire organ of *Gymnotus*, as compared with that of *Torpedo*, to be 128 : 1.

Du Bois-Reymond brought forward the following conclusions as evidence that the molecular hypothesis, in the same form in which it was drawn up for muscle and nerve, accounts for the E.M.F. of the electrical organ also (*l.c.* p. 288 f.): "The E.M.F. of a dipolar molecule from a regularly constructed test-muscle, as diminished by short-circuiting, = the double P.D. between equator and poles of the muscle, about 0·15 D. Let it be taken for security sake as = 0·10 D. The diameter of the *Gymnotus* plate, inclusive of the papillæ (which are also regarded as electromotive), as compared with the diameter of the *Torpedo* plate = 8·2 : 9·6 = 8·5 : 1; the first contains 8·5 times as many molecules as the second. *Two molecules alone,* one behind the other, of the *Torpedo* plate yield a total E.M.F. of 400 × 2 × 0·10 D = 80 D, which is sufficient. In *Gymnotus* we reach the formidable value of 6000 × 17 × 0·10 D = 10,200 D." According to Schönlein (*l.c.*), the highest E.M.F. that has yet been calculated for the discharge of *Torpedo* = between 30 and 31 D. The calculation was made "either by comparing the deflection from the discharge of the organ with that from a number of Daniell cells, introduced, with the addition of a resistance approximately equal to that of the organ, into the circuit in place of the organ, or by compensation" (Schönlein). If with Fritsch we reckon the number of plates in *Torpedo ocellata* at 370, in *T. marmorata* at 380

per prism, this gives us for each single plate an E.M.F. of $\frac{30 - 31}{370 - 380}$ D = 0·081–0·084 D.

These values are undoubtedly of quite a different order from those given for the E.M.F. of cold-blooded nerves, which is always below 0·025 D. On the other hand, it is a striking and hardly adventitious fact that the figures for the E.M.F. of the discharge from the plate, and the maximal negative variation of the muscle, are not merely of the same order, but are identical, whence Schönlein (*l.c.* p. 501) concludes that "the substratum at which the discharge of the electrical organ of *Torpedo* is completed may be identified exclusively with the substratum in which the negative variation of the muscle completes itself."[1] The hypothesis that there is any change of position of preformed electromotive molecules in the discharge, seems, however, under all conditions to be excluded, from the fact that the majority of electrical organs are no more than transformed muscles, and that the molecular theory has been disproved in regard to the latter. This is obviously not the place (since we are here concerned solely with the summary of the data so far contributed to the physiology of electrical fishes) to go beyond the intentions of the founder of the alteration theory, and attempt from that standpoint to explain the phenomena. It is, however, permissible to say that, in the opinion of the author, Hermann's theory is as well adapted to cover the new department (which merely, as it were, contains old matter in a new garment) as it proved to be in regard to gland and plant currents.

From this standpoint the principal interest attaches to *chemical processes* within the active substance proper of the electrical organ; it is well, therefore, to subjoin a few remarks on this subject, more particularly as comparing these with the corresponding reaction of striated muscle, since this is the material whence develops the electrical organs.

That the activity of muscle is correlated with chemical processes is shown *inter alia* by the fact (first pointed out by du Bois-Rey-

[1] More recently, on the other hand, Schönlein has adopted the view that the electrical plate is a "*nerve-ending*" (analogous with the motor end-plate). The electromotive substance of the muscle would then have entirely disappeared (which is certainly not the case in *Raja*).

mond) that the reaction differs in resting, and in excited as well as in dead muscle. The acidity is in the latter case so striking that it is easily demonstrated by less sensitive methods. In the electrical organ (of *Torpedo*) it is quite otherwise, as proved by repeated observations of many authors who have investigated this point. Boll (5 *a*), who, like du Bois-Reymond, tested the reaction with litmus-paper, found it unmistakably alkaline in the *non-excited* organ (*Torpedo*), and all later investigators have agreed with him (cf. Th. Weyl, 36 *b*; W. Marcuse, 20). As regards post-mortem acidity there is not, however, the same consensus of opinion. While Boll and Weyl convinced themselves of its appearance, Marcuse emphatically denied it. M. Schultze, again, found that the electrical organ of freshly-killed torpedoes was constantly very acid, which from analogy with the muscle was referred both by Funke and du Bois-Reymond to an exhaustive effort of the muscle previous to death, resulting from its frequent discharges. Experimental results are, again, in direct contradiction with this statement, neither strychnine poisoning, nor direct stimulation of the electrical lobe, nor cutting-off the blood-supply being successful in producing any marked degree of fatigue. Boll found none; Marcuse, who determined the reaction of the alcohol extract by titration, with litmus-paper, detected only the merest shade of difference between excited and non-excited organ (isolated by section of the nerve), the second state being slightly more acid than the first.

Röhmann (29), who has recently repeated these investigations at the zoological station at Naples, employed a method first invented by Dreser (*Cbl. f. Physiol.* i. 1887, p. 195) for muscle. This is based on the property possessed by acid-fuchsin, of forming with the alkali of the tissue fluids a colourless combination, which breaks up again with quite weak acids (even CO_2), and assumes a reddish colour. "If, after ligaturing the circulation (in a frog), the sciatic nerve on one side is tetanised intermittently (after previous injection of acid-fuchsin), there will (in 10–15 minutes) be a pronounced reddening of the excited limb, which on the ground of the chemical properties of the acid-fuchsin is a proof of the production of acid by active muscle" (Dreser). Röhmann was able to establish a similar reaction in the electrical organ, since in a torpedo injected with fuchsin, and strychninised, or persistently excited from the lobe,

the resting organ (isolated by division of the nerve, the skin having been removed) will be colourless or faintly pink, while the excited organ varies from pale pink to peach blossom colour. It must thus be taken as proven that "during the generation of electricity within the electrical plates there are alterations of metabolism which lead to the production of a small quantity of acid substances." On the other hand, Röhmann, like Marcuse, finds no increase of the nitrogenous extractive, or substances contained in the ether extract. Any participation of carbohydrate (glycogen) in the generation of electricity seems excluded by the fact that Marcuse finds neither glycogen nor any similar carbohydrate in the electrical organ.

"It is far more probable that a substance closely related to the albuminous bodies is the source of electromotive energy, and liberates it in the formation of acids which are soluble in ether" (Röhmann). It is above all remarkable that, according to the foregoing experiments, "the production of the electrical discharge of *Torpedo* seems to occur with the consumption of a minimal quantity of potential energy," which for the rest holds good equally of muscular work, though not in the same degree.

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CHAPTER XII

ELECTROMOTIVE ACTION IN THE EYE

ALTHOUGH subjective observation and the analysis of sensations must under all conditions take first rank among the methods of investigating the physiology of the senses, the objective signs of sensory activity, though scanty, are no less deserving of consideration. It is true that the great expectations associated at first with the discovery of visual purple, and the bleaching of it by light, have not hitherto been fulfilled, and the later endeavours of König and v. Kries to attribute a predominant *rôle* to this " visual substance " must be regarded as discredited.

Along with the " photo-chemistry " of the retina, its electromotive action and the alterations thereof by light stimuli claim the chief share of attention.

As early as 1849 du Bois-Reymond investigated the electrical reaction of the optic nerve, at its peripheral expansion in the eye, while he was engaged in proving the identity of the " natural " and artificial cross-section in nerve — as already established for muscle. On leading off from the artificial section, or from some point near it of the natural long section, of the optic nerve, and the external surface (*e.g.* cornea) of a fish's eyeball as free from muscle as possible, the nerve was invariably negative to the eyeball. The natural ending of the nerve thus seems no more positive than the tendon end of the muscle-fibres.

Sixteen years later, Holmgren (1) repeated these experiments, using principally the frog's eye. He confirmed the observations of du Bois-Reymond in regard to the " current of rest," and found, moreover, on leading off from the posterior portion of the bulb and the optic nerve, that the former was weakly negative to the latter. " If one electrode is applied to the optic nerve

while the other is moved, touching now the back of the bulb and now the cornea, there results in the first case what Holmgren calls the 'weak reaction,' where the optic nerve is positive to the eyeball, in the second the 'strong reaction,' nerve negative to cornea." Holmgren rightly observes that retina can no more than muscle be termed the "natural cross-section" of the correlated nerve, since it forms both anatomically and physiologically an end-organ distinct from the nerve, capable conceivably of independent electromotive action, like muscle or glands, under certain conditions. If, therefore, in agreement with du Bois-Reymond's view, we are still to speak of natural transverse and longitudinal sections, the former must be defined as the entire, external, mosaic surface of the retina, bordering on the choroid, while the inner boundary (layer of optic fibres) facing the vitreous body forms the natural long section. Holmgren determined the distribution of potential upon the surface of the bulb with great accuracy, and endeavoured to bring the retinal current into line with du Bois-Reymond's law of the muscle current. Without entering into detail, it may be said that, as we should anticipate from the electromotive action of the entire eye, there are in the retina differences of potential in the direction of an "ingoing" current (*i.e.* from without, inwards), signifying, in du Bois-Reymond's sense, that the natural cross-section (rods and cones) is negative to the natural long section (internal surface of the retina).

The inadmissibility of such an interpretation is, however, obvious if we consider the structure of the retina, which, as justly remarked by Kühne and Steiner, "exhibits throughout, and exclusively in the most external layer, objects that are quite unlike free nerve-endings, while in no other layer is there anything resembling such endings."

Kühne and Steiner (3) principally employed the isolated retina of the frog in their successful researches. This tissue may be slipped out of the fundus as out of a shell, with or without pigment epithelium, its vital properties being preserved intact, after which it can be drawn over a rounded glass rod, and brought into contact with the leading-off electrodes. If the rod-surface is external, and different points of the same are tested, there is invariably a strong current between the entrance of the optic nerve and the periphery, the former being

positive to all other points of the retina. In leading off, on the other hand, from the fibrous layer (internal surface), the entrance of the optic nerve is invariably negative to every peripheral point. Like Holmgren, Kühne and Steiner further observed, on leading off simultaneously from internal and external surface of the fresh retina, an "ingoing" current, the former being negative to the latter. The retina was so arranged between the electrodes "that the lower of the two supported the membrane on a clay cap curving upwards, while the other made contact with the opposite surface of the retina by a blunt point." The E.M.F. of this current, which is at first considerable, diminishes rapidly, and at times disappears completely, although in most cases it remains for some time longer at a medium height.

The variations of the retinal current under the influence of light are of far greater interest than its intrinsic behaviour. Here, again, it is to Holmgren that we owe the fundamental observations: he showed that the retinal current invariably gives a positive deflection, if light falls on an eye that had previously been in the dark, or when light is shut off from it. This occurs in the frog without exception, while in reptiles (snakes), birds, and mammals Holmgren finds on the contrary a negative effect at the impact of light, a positive variation at darkness. The mere alteration of intensity of illumination makes an effective stimulus.

Dewar and M'Kendrick discovered, independent of Holmgren, that a positive variation resulted from illumination of the eyes of vertebrates (of all classes), as also of crustacea, corresponding to an increase of E.M.F. in the rest-current of 3–10 %. During part of the experiments the lead-off (frog) was not merely from the bulb, but from this, and a portion of the brain still connected with it by the optic nerve. Here, too, the impact of light was followed by a strong positive variation. The same occurs in the pigeon on leading off from optic lobe and cornea of the opposite eye. The variation in this case is nearly doubled if the two retinæ are simultaneously illuminated, nor is it altogether absent on leading off from lobe and cornea on the same side. Of coloured lights, yellow was the most effective, then came green, red, and blue. Lastly, Dewar and M'Kendrick eventually believed that they had discovered relations between stimulus and effect, corresponding with Fechner's law.

Kühne and Steiner (*l.c.*) at first experimented in a dark room divided into three parts. The two farthest contained the galvanometer and telescope, while the eye was prepared in the third room by a lamp. In the later experiments the galvanometer was placed in a light room, while the electrodes and illuminating arrangements were in an adjacent and absolutely dark chamber. The stimulus was made by an Argand gas-burner at a distance of 50–75 cm. from the preparation. The lamp was turned up and down by an assistant at a signal, so that the retina was suddenly illuminated or darkened. The lead-off from the inner and outer surfaces of the retina was effected by specially constructed clay electrodes, covered (Engelmann's method) with frog's lung. Each adequate and sudden illumination with blue, green, yellow, red, or white light then produced a considerable complex variation of the retinal current, with or without the presence of visual purple. The typical effect (Fig. 282) in a retina containing the purple is a positive variation at the moment of illumination (*b c*) rising rapidly to its maximum, and then passing quickly into the negative variation. This phase reaches its maximum (*d e*) during the impact of light, is delayed some time at this point, and then declines very gradually to zero, even during constant illumination. At the moment of darkness there is again a sudden positive effect (*e f*), which must be regarded as the result of a second stimulus due to the disappearance of light. The mode of excitation is therefore in a measure comparable with that from an electrical stimulus. As in the latter, the impact and duration of the current on the one hand, and its disappearance on the other, act as a stimulus, so with the impact of light upon the retina, where the effects are visible on the galvanometer as an initial diphasic (positive then negative) and a second simple (positive) variation of the rest-current. The presence or absence of visual purple appears from Kühne and Steiner to be of essential importance to the intensity of the retinal "current of action." Not merely does the magnitude of the variations differ in the two cases, being greater in the unbleached retina

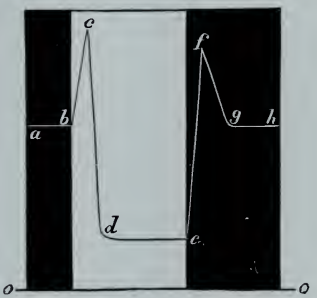

Fig. 282.

for the same stimulus, but they are qualitatively different. In "light" frogs—such, *i.e.*, as have been exposed for hours to the full effect of daylight—the positive fore-swing of the negative variation concomitant with the impact of light is entirely wanting, or appears as a trace only. The same reaction, according to Kühne and Steiner, is exhibited by the retinæ of winter-frogs even when confined for days in darkness in a warm room.

If the current of rest in an unbleached "dark" retina is of low E.M.F., and the negative variation in illumination only moderately developed, there is usually a reversal of the current at excitation, immediately after the positive fore-swing, which lasts throughout the period of light (Fig. 283). In other cases

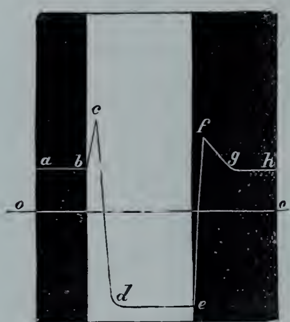

FIG. 283.

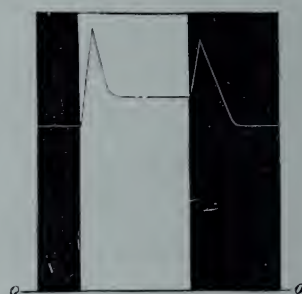

FIG. 284.

(with a strong current of rest), there is often no genuine negative variation, merely a more or less considerable decrement of the preliminary positive fore-swing (Fig. 284). The current of rest often begins to sink rapidly from the moment of preparation. It may not merely sink to zero, but be reversed. The photo-electric variations are only thereby affected in so far that the individual phases collectively exhibit the opposite signs, while entry, order, course, and magnitude undergo no alteration. The three variations accordingly present the indices $-\ +\ -$, instead of the normal $+\ -\ +$.

The fact that the three phases of the retinal action current, due to transitory illumination, appear in sensitive preparations even when, as with the electric spark, the impact of light is momentary, shows that the medium negative phase must not be regarded merely as the consequence of *permanent* illumination,

since it is just this phase which *alone* appears in less excitable preparations with instantaneous light stimuli.

It is further remarkable that, as was found by Fuchs (4), "the first (positive) phase of the variation produced by the electric spark occurs incomparably more rapidly than in non-instantaneous illumination." This is a strong argument for considering the (photo-electric) variations as the expression of the excitatory process in the sensory matter" (S. Fuchs).

Every considerable variation in intensity of illumination produces, indifferently as to whether it occurs in the negative or the positive direction, a *positive* variation of the rest-current; as expressed on leading off from the isolated retina by twitching movements, if the flame is made brighter or darker by turning the gas up or down. "And since our eyes cannot perceive such increments above a certain limen of intensity, the movements on the galvanometer cease just before the highest luminosity is attained" (Kühne and Steiner).

The retina is extraordinarily sensitive towards even the merest trace of light (glimmer of a cigarette, flash of phosphorescent powder), so that it may be said, on the ground of Kühne and Steiner's experiments, that the galvanometer reacts to the same intensities of light "that produce a clear sensation in the eye." If the illumination is confined to the smallest possible point of the retina, there is none the less a photo-electric variation at every other point, however distant, due either to currents deriving from the tract that is directly illuminated, or to the effect of diffusion of light in the retina.

The effect in the entire, uninjured eyeball differs essentially from the course of the photo-electric variation in the isolated retina as described above, since in preparations of maximal excitability the second negative phase of the variation upon the impact of light is wanting: so that even when the illumination is protracted for several minutes there is a uniform increase between the first positive initial and second equally positive terminal variation of the current. An effect analogous to that in the isolated retina appears only with injured, fatigued, or dying bulbi (which may be compared with certain observations of Dewar and M'Kendrick).

The variations of the eyeball current are further much smaller, in consequence of the less favourable conditions of

leading off, and may after previous, strong illumination fail altogether, while the isolated retina would still yield a vigorous current of action.

These differences in the photo-electrical variations of the eyeball and isolated retina appear to derive solely from unavoidable alteration of the latter during preparation, since careful division of the eye into anterior and posterior halves, with removal of the lens, never produces the middle, negative phase, while this never fails to appear on tearing the retina, or letting out the vitreous humour. The same occurs in the uninjured eyeball, when excitability diminishes gradually in a stale preparation (accumulation of CO_2). The positive initial phase of the diphasic variation becomes gradually smaller, and at last fails altogether. Holmgren was the first to observe the differences in the photo-electrical variations of the retinæ of various animals. In reptiles (*Vipera Berus*), birds (fowl), and mammals (rabbit, dog), the uninjured eyeball *in situ* invariably exhibits first a negative and then a positive variation of the current of rest, instead of the diphasic—in both cases positive—variation of the frog's eye at the commencement and end of illumination. Since (*supra*) a similar reaction takes place in dying or fatigued frogs' eyes, the effect might presumably be due to the lower resistance of warm-blooded eyes, on the assumption that if investigated under conditions as nearly as possible normal, they would exhibit the same characteristics of photo-electrical variation as the frog's eye. Against this, however, we have on the one hand the fact that in certain cases, *e.g.* the pigeon (where the long rods and cones are very enduring), the isolated retina lends itself readily to experiment, and plainly shows at least the initial negative phase (especially if the temperature of the chamber is raised a little, Kühne and Steiner): on the other hand, the reaction of reptiles' and still more of fishes' eyes may be urged as a plausible objection.

The results of illuminating the fish's eye were *nil* for Holmgren, and very unsatisfactory to Dewar and M'Kendrick. Kühne and Steiner, on the contrary, obtained successful effects from the uninjured eyeball, and still more from the isolated retina of several species of fish (*Perca fluv.*, *Esox lucius, Leuciscus* and *Cyprinus barbus*).

While the current of rest gives the same reaction as in the

frog—*i.e.* greatest in the uninjured eyeball, least, and often reversed, in the isolated retina—the photo-electrical variations are essentially different in character and distribution (Fig. 285). In the eyeball there is at the commencement of illumination a positive and very slowly increasing variation, that only rises abruptly at the end to its maximum. This is succeeded by an increase of the current of rest which persists during the impact of the light, and at the close of illumination is followed by another, but much weaker, positive variation. On the other hand, the posterior half of the eye, as also the isolated retina, yields an initial *negative* variation, followed immediately by a positive phase, in which the current of rest is more or less augmented beyond its original proportions. At cessation of light there is, as in the frog, another *positive* variation of considerable magnitude. If any alteration occurs in the retina, the current of rest will not, at the close of the first negative phase, regain its original base-line during the illumination—while finally, in fatigued or dying preparations, a decrement of the negative variation fails altogether, so that this phase remains as the sole effect of excitation.

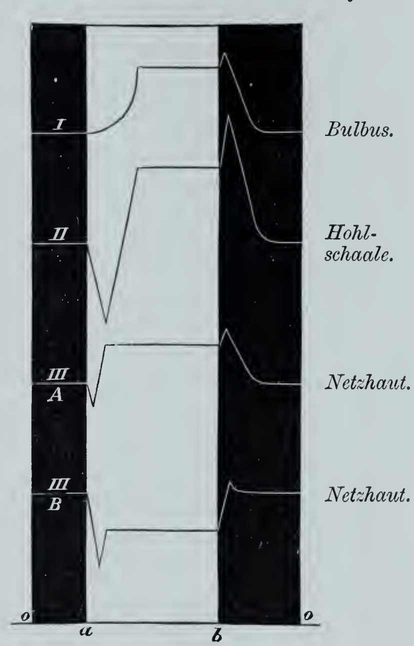

FIG. 285.

Van Genderen-Stort (5) observed that the movements (change of position) in the cones of the retina, as well as the displacement of pigment in the retinal epithelium, were produced not merely by the direct illumination of that eye, but also by illumination of the other; whence it might be concluded that the optic nerve contains not merely sensory but also centrifugal (retino-motor) fibres. Engelmann has shown (5) that this might incite reflex alteration in the electromotivity of the eyeball. Obvious variations were obtained in every instance, on leading off

from the middle of the cornea and a point posterior to it or near the equator, in the upper half of the eyeball of a " dark " frog, when (with complete obscurity of this eye) the other eye was illuminated. The same occurred after removal of the skin as well as of the mucosa of the palate, although in a lesser degree. In opposition to the photo-electrical variations with direct illumination, absence of the second positive phase occurred only with sudden obscurity. After dividing the optic nerve, there was no galvanic effect from illumination of the opposite side. Chemical stimulation (application of a crystal of salt to the retina of the opened eyeball) produced considerable variations of the rest-current in the other eye, first in the positive and then in the negative direction.

Starting from the experiments of Kühne and Steiner upon *instantaneous* illumination of the retina, Sigm. Fuchs (4) has recently been attempting to determine more exactly the time-relations of the photo-electrical variations in the frog's eye, and to discover whether (as might be anticipated) the excitation of the apparatus of the optic nerve, and therewith of the accompanying light sensation, occurs subsequently to the stimulus which discharges them. A series of opening sparks were discharged by means of Bernstein's rheotome as adequate stimuli for the retina, the galvanometer being closed, on the other hand, at a variable interval after each impact of light.

The form and time-relations of the curve of variation could thus be investigated by the same method as the negative variation of the muscle or nerve current. The experiment was of course performed after compensating the current of rest. Kühne and Steiner had previously made observations upon the E.M.F. of the latter, which are approximately confirmed by the valuable data obtained by S. Fuchs with the Poggendorff-du Bois-Reymond method of compensation.

The E.M.F. of the current of rest during a single experiment was sufficiently constant to give assurance that the conditions underwent no substantial alteration during the period of investigation. Each rheotome experiment started " from the appearance of the spark at the moment of opening the retina circuit in the rheotome. The characteristic position of the slider must be regarded as the zero-point, from which the experiment starts each time, or to which it returns." Under these conditions

there was never an effect upon the galvanometer, since the photo-electrical variation occurred during the period of an entire revolution (0·2564 sec.). It further appeared "that a measurable period (0·0005–0·0060 sec.) elapsed between the moment of stimulation and the perceptible commencement of the positive part of the variation, after which the positive preliminary phase rapidly attains its maximum, and then falls quickly, passing into the negative portion of the photo-electrical variation. If this latter makes its appearance alone, with no positive fore-swing, a stage of latent excitation (from 0·0004 to 0·0064 sec.) is still plainly visible, followed first by a weaker phase (negative fore-swing) and then by the true negative principal variation. The maximum duration of the positive fore-swing lasts, according to Fuchs, 0·0181 sec.; the minimum = 0·0070 sec. The negative fore-swing lasts (with exclusive appearance of the negative variation) between 0·0029 and 0·0105 sec.; the period to the maximum of the negative variation = 0·0089–0·0352 sec.

The question may be raised as to what portions (layers) of the retina are mainly or solely concerned in initiating the electrical P.D. The exclusive appearance of the *negative* variation at the trunk of the optic nerve on stimulating the eye with light, permits us to conclude with tolerable certainty that the anterior fibrous layer gives a similar reaction, whence it follows that the processes underlying the complex photo-electrical variations of the retina are situated in layers that do not extend anteriorly beyond the ganglion layer. That this layer is not itself directly implicated appears from the fact that retinal preparations from warm-blooded animals are usually very unstable, and quickly lose their photo-electrical reaction even when the whole fundus of the eye is examined. This must be referred to the well-known sensibility of non-ganglionic elements to all disturbances of their normal metabolism. The *high resistance of the bird's retina* is therefore the more remarkable. Kühne and Steiner obtained good results with even the isolated retina (pigeon), which can only be referred to the great vitality of the long rods and cones in the pigeon, since it can scarcely be supposed that ganglion-cells or nerve-fibres of the retina would be excitable 45–50 min. after making the preparation. We are thus forced to conclude that the

epithelial elements (*the true sensory cells*) *are again the seat of electromotivity*, which is the more probable since it can be shown that the changes produced by light are initiated in these elements. According to Kühne and Steiner, however, this is due less to primary photo-chemical processes occurring in the external elements of the visual cells—the alteration of the hypothetical visual substance by light — than to the consequences of excitation of "the protoplasm contained in the internal constituents of the visual cells, by the photo-chemical products of disintegration."

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I. p. 113. 75. SCHENCK. Ueber die Gipfelzeit bei summirten isotonischen u. isometrischen Zuckungen. P. A. LXIV.

I. p. 319. 49. ROUX. Ueber die polare Erregung der lebendigen Substanz, etc. P. A. LXIII.

50. VERWORN. Untersuchungen über die polare Erregung der lebendigen Substanz durch den constanten Strom. P. A. LXII. and LXV.
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I. p. 517. 91. HERMANN. Das Capillar-Elektrometer u. die Actions-ströme des Muskels. P. A. LXIII.

92. BERNSTEIN. Zur Theorie der Negative Schwankung. P. A. LXVII.

93. SCHENCK. Ueber den Einfluss der Spannung auf die "negative Schwankung" des Muskelstroms. P. A. LXIII.

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2. Graphische Rheotomversuche am Nerven, Kernleiter, u. Muskel. P. A. LXIII.
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INDEX[1]

[1] The translator is responsible for the subdivision of chapters, and enlargement of index, in this volume.

THE END

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ERRATA IN VOL. I

Page xi., *insert* Cross-striated, Multinuclear Muscle Fibres, page 26, *after* The Muscles of Metazoa.

Page xii., *insert* The Electrical Excitation of Muscle, page 174, *above* The Electrical Excitation of Unfibrillated Protoplasm.

Page 3, line 4 from bottom, *for* Acanthocystiden *read* Acanthocystidæ.

Page 4, line 16, *read* Opalinidæ.

Page 18, line 3, *for* bisected *read* when cut across (*and transpose to end of line*).

Page 29, lines 11, 13, *for* areæ *read* areas, *passim.*

Page 46, line 25, *for* refractibility *read* refracting power.

Ib. line 32, *read* refraction.

Page 47, lines 32, 40, page 48, line 14, *for* double refractibility *read* double refraction.

Page 47, line 27, *insert* in *after* dark.

Page 49, lines 17, 18, *for* accept the penetrating conclusions *read* follow the admirable researches.

Page 56, line 19, *for* abscissa *read* base-line ; *ib.* page 116, line 8 ; page 146, line 12 ; page 205, bottom line ; page 364, 5 from bottom ; page 366, 11 from bottom ; page 375, 12 from bottom.

Page 58, line 16, *delete* elementary ; line 27, *ib.*, *and for* an elementary *read* a simple.

Page 68, line 26, *for* muscles *read* mussels.

Page 70, line 24, *insert* only *after* cardiac muscle.

Page 80, lines 11, 14, and *passim*, *for* canula *read* cannula.

Page 81, line 28, *for* while at the same time *read* although.

Ib. lines, 36, 37, *read* and at the same time to give a graphic record of its varying tension.

Ib. line 38, *for* the short *read* a very short.

Page 82, line 8, *insert* the *before* muscle.

Ib. lines 14 and 8 from bottom, *insert* quotation marks *before* The, *and* (Fick 39) *after* tension.

Ib. lines 6 and 5 from bottom, *read* with the greatest possible tension the muscle only shortens by a.

Ib. line 3, *insert* during *before* its contraction.

Page 97, line 24, *insert* in muscle *after* death.

Ib. line 25, *for* denoted *read* readily explained by the ; *for* products *read* processes.

Page 98, 4 from bottom, *for* at a moderate rate *read* by a suitable rate.

Page 99, line 6, *for* by *read* in.

Page 102, line 15, *for* i.e. *read* namely ; line 18, *for* or *read* of.

Page 103, line 17, *read* This tonus may be at once abolished.

Ib. line 19, *for* reduces *read* disappears.

Page 107, line 7, *insert* comma *after* fall.

Ib. line 14, *for* Na_2CO_2 *read* Na_2CO_3.

Page 109, bottom line, *insert* the *before* sartorius.

Page 110, line 10, *delete* and, *read* so that the twitches, usually of very brief duration, served up, etc. ; line 11, *for* abscissa *read* abscissæ.

Page 114, line 22, *for* tetanus *read* tetanic ; line 28, *for* behind *read* near.

Page 115, line 3, *read* interval between the two stimuli is equal to the period of rising energy of a single contraction.

Ib. line 11, *for* scheme *read* schema ; line 13, *read* vertically over.

Page 116, line 11, *read* according as the second twitch was superposed at a more advanced stage of the first contraction.

Page 117, line 13, and *passim*, *for* crab *read* crayfish.

Ib. last line, *for* tetanus *read* tetanic.

Page 120, line 9, *ib.*

Ib. Fig. 54 should be reversed.

Page 121, line 24, *for* the *read* a loaded muscle.

Page 122, last line but one, *for* proportionately *read* suitably.

Page 128, line 27, *for* 250 *read* 280.

Page 130, line 7, *read* stimuli and contractions ; line 8, *for* working *read* sent in.

Page 131, last line, *read* As regards strength of current, the rhythm was limited between just effective distance of the coils, and 1–2 mm. ; in other words, to a very small interval of difference.

Page 134, line 6, *for* over *read* by ; last line, *insert* only *after* systole.

Page 136, line 17, *for* since *read* and.

Page 137, line 14, *insert* to *before* which.

Page 139, line 9, *delete* comma *after* registered.

Page 144, No. 38 of Bibliography, *tr. into* Griffiths.

Page 148, last lines, *for* pseudopod *read* pseudopodium (*passim*).

Page 149, 3 from bottom, *for* sense *read* direction.

Page 152, line 6, *for* excitating *read* exciting.

Page 174, line 9, *for* momentary *read* instantaneous.

Page 182, line 3, *for* in *read* with ; 5 from bottom, *for* between *read* in.

Page 193, line 28, *for* steepness *read* abruptness.

Page 195, line 5, *for* in *read* within ; line 27, *insert* (Biedermann, 14).

Page 219, line 3, *for* less *read* more.

Page 221, line 9, *for* potash *read* potassium (*passim*).

Page 299, line 10, *read* Becquerel (*passim*).

Page 310, line 23, *for* areæ *read* areas.

Page 320, line 3, comma *after* mass motion ; and line 4, *insert* in *before* electricity.

Page 333, line 9, *for* spurious *read* false *or* supposititious.

Page 338, last line, *read* albumin ; page 340, line 25, *ib.*

Page 358, line 9, *for* sense *read* direction ; line 26, *for* i.e. *read* e.g.

Page 371, line 4, *for* negative variation *read* single negative phase ; line 28, *for* record *read* representation.

Page 372, 1 from bottom, *for* free *read* light.

Page 376, line 20, *for* was the precursor of *read* preceded the.

Page 384, line 24, *for* Doyer *read* Doyère.

Page 385, line 25, and page 386, lines 7, 27, 29, *for* achilles *read* achillis.

Page 510, lines 4, 14, 36, and *passim*, *for* hilus *read* hilum.

SECONDARY ELECTROMOTIVE ACTION IN MUSCLE

Chapter IV., Section IV. (Revised)

Read, In muscle (as in nerve, electrical organs, and irritable protoplasm in general) the passage of the electrical current is followed by certain electromotive reactions, which are intimately related with the action current, and are to a certain extent only a special manifestation of the same. As early as 1834, Peltier discovered that the protracted passage of current in frogs' limbs, in isolated muscles, and even in pieces of muscle, will develop a current in the reverse direction. This he interpreted to mean that oxygen and hydrogen are separated at the interface of animal tissue and conducting fluid, as they would be at an intermediate metal surface.

Du Bois-Reymond (67), who took up the investigation later, came to the conclusion that the secondary current (after-current) does not depend exclusively, if at all, upon the ions separated at the poles, but is also generated in the tract lying between them. He found, namely, that all sections of the intrapolar tract of a longitudinally-traversed muscle will give electromotive action in the same direction, after opening the polarising current. Accordingly, he advanced the view that this effect mainly depended on what he termed "*internal polarisation*."

Many inorganic and organic porous bodies, saturated with an electrolyte, do, in fact, acquire the property of *negative* internal polarisation. The polarising current then divides itself between the badly-conducting, saturating fluid, and the porous vessel, when the latter becomes polarised from the separated ions. "Each of the many interfaces now gives electromotive action in the reverse direction from that in which it was traversed by the current." The superposition of all these partial currents results in a current through the circuit. Each tract of equal length in any regularly constructed (prismatic, or cylindrical) body will, as a rule, exhibit marked secondary electromotive action after the passage of the current.

Soon, however, it was observed that living muscle, traversed by the current, behaved in this respect quite differently from dead organic, or inorganic, bodies; as shown, above all, in the fact that *positive, as well as negative, after-currents* make their appearance under certain conditions. For the investigation of polarisation effects in muscle, du Bois-Reymond generally employed the *gracilis* and *semimembranosus* muscles, at a convenient tension. He used one pair of unpolarisable electrodes to lead in the polarising current, and another to lead off the polarisation current. The latter were usually placed between the first pair, within the intrapolar

tract. A special contrivance enabled him to alter the "period of closure"—*i.e.* the time for which the polarising current was sent through the polarisable object—from 0·001–20 secs. The same contrivance effected closure of the galvanometer circuit, after breaking the battery circuit at a minimal and constant interval.

The resulting secondary electromotive effects in the muscle are essentially dependent on the density and duration of the primary current, and are very confused, owing to the constant interference of negative and positive effects. "With a current density below that of 2 Groves, and with a very brief closure, no polarisation is, as a rule, perceptible on the galvanometer. The first traces obtained with 1 Dan. and 1 sec. closure are negative. The first positive traces appear with 2 Groves, and about 0·3 sec. closure."

With increasing period of closure, du Bois found that positive polarisation quickly reaches its maximum, and then declines more slowly, and passes over into negative polarisation, which again rises to a maximum. He fixes the "critical point" of closure as that at which positive passes into negative polarisation. The maximal positive polarisation in these experiments was at a closure of 0·075 sec. with 20 Groves (!); the maximal negative polarisation at ten minutes' closure of 1 Grove. Brief impacts of current (induction shocks) invariably produce positive polarisation only.

Both positive and negative polarisation are very persistent, and sometimes outlast the opening of the polarising current for twenty minutes or more. If the current is broken at the "critical point," du Bois not infrequently observed a diphasic effect, usually in the direction of first negative and then positive polarisation. This is due to the fact that, while *both* polarisations are simultaneously present from the moment of closure, they increase in a different degree, "negative polarisation rising more in proportion with the time of closure, while positive polarisation rises quickly at first, and then more slowly."

Du Bois-Reymond further concluded from experiments in which the upper and lower half of regularly-constructed muscles were traversed alternately by the current, and tested for polarisation, that "strong positive polarisation is exhibited in the upper half with ascending, in the lower half with descending direction of current."

Dead muscles still exhibit traces of negative internal polarisability, that are completely abolished only by boiling; positive polarisation, on the contrary, is exclusively characteristic of living muscle.

Du Bois-Reymond concluded, "not that electromotive forces homodromous with the primary current are generated by the positively polarisable tissues, but that the carriers of pre-existing electromotive forces (electromotive molecules) are homodromously adjusted with the primary current."

How little these results really support the molecular theory, is obvious from the later investigations of Hering and Hermann (68, 69).

In the first place, Hering proves conclusively that there can be no question of *internal* positive or negative polarisation in du Bois-Reymond's sense, since the actual seat of the electromotive changes induced by the exciting current is at those points of the contractile substance by which the current enters or leaves the muscle (the physiological poles): so that the close relation between these phenomena and the polar action of the current is unmistakable.

If (as already set forth) each alteration of chemical activity in any part of the muscle-fibre necessarily implies the appearance of electromotive action, we should anticipate that on sending current through a muscle with parallel fibres, the chemical alterations in the contractile substance at the physiological kathode and anode would initiate differences of potential. And these differences must be manifested when one or the other end, so altered, of the muscle is led off in connection with a point on the otherwise uninjured surface. The results which Hering obtained from experiments on the frog's sartorius did, in fact, correspond in every particular with this assumption.

If, namely, this muscle is fixed at moderate tension, the current being passed through it from the stumps of bone on either side, then on leading off from one or the other tendon-end, and from a point on the longitudinal surface, the muscle current measured previous to the passage of the current will, on breaking the latter, be found to be considerably altered. It is increased, diminished, neutralised, or the reverse, according to the direction, strength, and duration of the exciting current, and the strength and direction of the original muscle current. When the muscle current has been previously compensated, "polarisation currents" make their appearance in correspondence with the positive or negative modification of the muscle current. These may be positive or negative, *i.e.* homodromous or heterodromous to the exciting current. Since they are really initiated at the anodic and kathodic points of the muscle-substance, Hering distinguishes between *anodic* and *kathodic* polarisation. The former may be either positive or negative, the latter is in most cases negative only.

With a brief closure, very weak currents invariably give a *negative* polarisation current in fresh muscle, so long as only the anodic tendon-end, and a point at about the middle of the muscle surface, are in the galvanometer circuit. With stronger exciting currents, on the other hand, and not too brief a closure, *positive* polarisation alone results, and increases with the strength of current, until finally it far exceeds the strongest negative anodic polarisation.

Very strong currents produce positive polarisation at once, even with the shortest possible closure. Weaker currents, with brief closure, give negative or diphasic (first negative, then positive) polarisation, and the pure positive effect only appears after prolonged closure. Induction currents are like strong constant currents, with minimal closure, and produce positive anodic polarisation only.

All these polarisation effects (after-currents) are wanting, or at most appear as a trace, if both leading-off electrodes are applied to the longitudinal surface of the muscle, and not too close to one or the other end of it.

Since, according to Hermann's "alteration theory," excited muscle-substance is negative to unexcited substance, there can, when we consider the conditions and the character of the opening excitation in muscle, be no doubt that positive anodic polarisation is the expression of the latter. "*The positive polarisation current produced by alteration of the anodic points of the contractile substance is an action current, due to the break excitation starting from the anode*": *albeit, an action current that behaves very differently from the action current due to the make stimulus, that has so far exclusively concerned us.*

The long persistence of negativity at the anodic points is remarkable in

this connection. It is easily explained by the fact that the opening of a constant current leads, under certain conditions, to the protracted excitation (persistent opening contraction) of the muscle. This gradually declines, becoming more and more restricted to the anodic points of the muscle. Even, however, in cases where (as with weaker currents, or brief closure of strong currents) there is no *visible* persistent break contraction, nor even a break twitch, we are free to regard the positive polarisation current as the expression of a break excitation lasting for a considerable period—inasmuch as a low degree of contraction is difficult or impossible to demonstrate, especially when it is confined to the immediate vicinity of the anodic or kathodic points of the muscle, while negativity may be present as the expression of excitation, without the slightest manifestation of contraction.

Hermann's view of the positive anodic after-current only differs from that of Hering in that (starting with the assumption of an intrapolar electrotonus) he locates the break action current in the entire anelectrotonic tract of the muscle. But it has already been shown (*supra*) that, provided we avoid an undue strength of polarising current, the alterations that are termed collectively "electrotonus" are *all* strictly confined to the physiological electrode points.

With respect to *kathodic polarisation*, we find that it is almost exclusively negative in striated muscle. On leading off from a sartorius (through which current is passing) by the kathodic end, and centre, of the muscle, polarisation first appears, with very weak currents, after a closure of several seconds, and is steadily augmented with increased strength of current and longer closure. On comparing it with the positive anodic after-currents observed at the same end of the muscle, at the same strength of current and duration of closure, the latter soon exceed it very considerably. With very strong currents and prolonged closure, negative kathodic polarisation may become as strong as the equally abterminal muscle current seen on killing the same end of the muscle, without shifting the galvanometer electrodes. Induction currents also give negative kathodic polarisation, but it is essentially weaker than the positive anodic polarisation produced by the same strength of induction current in the same (sartorius) muscle. The conclusion is therefore that, *with increasing strength and duration of exciting current, the kathodic region of the muscle (physiological kathode) becomes more and more negative in comparison with the centre of the muscle.* If this effect were the equivalent of internal physical polarisation, the negative polarisation current would, as has been shown, appear at approximately constant strength on leading off from any point within the intrapolar tract; and Hering has shown that this never is the case. On the contrary, when the leading-off electrodes are placed at the boundary between the upper and middle thirds of the sartorius, while the polarising current is led in as before through the bones, there is either no polarisation current, or it is so insignificant in comparison with the anodic and kathodic polarisation that it is practically negligible. The relatively weak effects which may be observed in the intrapolar tract with very strong polarising currents, and prolonged closure, are to be explained by the fact that the *polar points* of the muscle are never confined exclusively to its ends, *e.g.* in the sartorius there are not infrequently short fibres which terminate, or begin, somewhere in the length of the muscle. Again, the appearance of the make and break persistent con-

traction necessarily produces inequalities in the individual parts of the interpolar tract. Hence, there is no adequate reason for assuming an internal polarisation of the muscle-substance in du Bois-Reymond's sense. *On the other hand, all the manifestations of negative kathodic polarisation are again readily explained by chemical alterations (excitation or local fatigue) in the kathodic points of the fibres collectively.*

Nor are the later experiments of du Bois-Reymond more convincing, in which the application of a current from 10 Groves produced, after 15-25 minutes' closure, "a secondary E.M.F. in the reverse direction to the polarising current, in every part of the muscle"—its magnitude increasing with the length of the tract led off. For the extent to which excitability and conductivity in the muscle would be altered by such impossibly strong currents is sufficiently attested by the appearance of the galvanic wave under similar conditions, as also by the persistent excitation (often extremely marked, and widely distributed over the intrapolar tract of the muscle) in the anodic region, which depends, as was shown above, upon the effectuation of secondary electrode points. Indeed there can hardly be a doubt, after the preceding discussion, that experiments performed under such abnormal conditions in no way contravene the clear and simple result of Hering's investigations.

The most striking proof that secondary electromotive phenomena are pure *polar* effects of the current is, however, the fact that both positive anodic and negative kathodic polarisation are abolished by killing the anodic or kathodic ends of the muscle, exactly as occurs with the opening and closing excitation. *The negative, and still more the positive, polarisation current is accordingly dependent upon the integrity of the kathodic or anodic points of the excitable tissues.*

Hermann points this out in reference to the positive anodic after-current only in muscle, designating this alone as "*irritative*," in contradistinction to the negative after-current "resulting from true polarisation." Like du Bois-Reymond, he derives the latter from the entire intrapolar tract, and after partial passage of the current from the extrapolar tracts also, in consequence of a polarisation which he takes to be equivalent with certain polarisation phenomena (to be discussed below; *see* vol. ii. pp. 309 ff.) that occur in medullated nerve—as also in a polarisable wire surrounded by an electrolyte, through the sheath of which the current enters. He concludes that the effects upon this core model coincide with the polarisation effects, both intra- and extra-polar, of muscle (and nerve), the "polarisation after-current" being in the first case heterodromous, in the second homodromous, with the polarising current.

We shall enter more fully into these relations in discussing the electrical excitation of nerve; for the moment it may be said that little as the phenomena can be disputed under some conditions, yet that in muscle (within a certain, so to speak, physiological limit of current strength) the negative kathodic must, equally with the positive anodic after-current, be designated as "irritative," and resulting altogether from pure *polar* action of the current.

Page 449, line 16, *for* has recently *read* subsequently.
Ib. line 24, *for* antagonistic *read* heterodromous.
Ib. line 30, *insert* designated as *after* is.

Page 449, line 35, *for* proper *read* itself.

Page 450, line 26, *for* no trace *read* only a trace.

Page 451, line 28, *after* the *read* presence of the alterations fundamental to the after-current.

Page 452, line 22, *for* exist *read* be manifested, *insert* quite *before* different.

Page 453, line 23, *delete* or *after* positive.

Page 459, line 19, *for* end *read* close.